A Framework for ICT-Supported Coordination in Crisis Response

Rafael A. Gonzalez

A FRAMEWORK FOR ICT-SUPPORTED COORDINATION IN CRISIS RESPONSE

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This book is dedicated to my family:
Carlos, Daniel, Elsa, Fernando & Isabel.

Colophon

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Preface and Acknowledgements

They say that the Chinese word for "crisis" can also mean opportunity. I've recently learned this is a myth, but there is indeed opportunity for improving our ability to respond to crises. In the current state of affairs, hurricanes, tsunamis, financial meltdown, food and water shortages, oil spills, climate change, pandemics, terrorist attacks and war, compete for our attention and resources. When such crises take place, coordination between different response professionals, agencies and volunteers is often cited as a major difficulty. With the ensuing uncertainty, some emergent behavior will arise, including assaults, looting, and migration, but also resulting in spontaneous coordination across *ad hoc* groups of responders. Actually, emergent coordination has raised considerable interest not just in the domain of crisis response, but in social and business contexts, where coordination can emerge inside social networks. Within the "information-processing view of organizations", Jay Galbraith had already emphasized the role that "lateral capabilities" have in achieving coordination. To support the creation of lateral capabilities within an organization, Galbraith and others offered several guidelines that are commonly used in the crisis response domain, such as communities of practice, training and annual meetings. Such guidelines suggest that for an organization to increase its chances to exhibit bottom-up emergent coordination, it would first have to put into effect top-down strategies to create the conditions for it. In crisis response, while such top-down pre-incident efforts are commonly pursued, they become more difficult as they encompass multiple disciplines, regions and types of incident.

As the "command and control" era is becoming obsolete, coordination is often enabled by information and communication technology (ICT). Accordingly, exploiting existing ICT for improved coordination during a crisis will become increasingly common place. However, given that the crises and their corresponding *ad hoc* crisis response organizations are still unknown, we have to rely on planning, training and simulation in order to increase our understanding and preparedness. In particular, using agent-based modeling and simulation is a suitable way to represent heterogeneous, autonomous crisis responders, enabling the simulation of aggregate behavior out of local agent behaviors. With such a model it is also possible to operationalize different coordination mechanisms that could be supported with ICT in order to compare and evaluate them in an artificial setting, before moving on to training, planning and actual use during a crisis. One such simulation model has been designed within this research project, together with the set of constructs, models and methods that went into its construction and experimental design. These artifacts provide a conceptual framework and the design knowledge required to build agent-based simulations for the study of coordination in crisis response.

This research was supported by various organizations and individuals to which I am grateful. Henk Sol advised me during the whole process, contributing his ample experience and keen insight to keep me on track, while allowing me the freedom to meander as well. Alexander Verbraeck devoted many long hours to discussing my research in depth, suggesting improvements and challenging me to always think beyond. With his support I became a member of the Systems Engineering section of the Faculty of Technology, Policy and Management in Delft. This was not only instrumental for carrying out my research and supporting my stay in The Netherlands and my trips to conferences, but also greatly stimulating and fun.

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R.G., Amsterdam, May 2010

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1 Towards ICT-Supported Coordination in Crisis Response

1.1 Introduction

Coordinating a highly trained, hierarchical, technology-proficient organization to execute a standard process is not the same as coordinating a previously unknown adhocracy of agencies that unpredictably enter and exit a new situation under time pressure and high risk. While current technologies that support coordination are successful for well-defined static process descriptions, they may fall short in the face of more complex and dynamic scenarios, such as a crisis or emergency. The following research contributes a set of design artifacts that are used to gain insight into coordination in crisis response and its support with information and communication technology (ICT). A simulation model, together with the constructs, methods and design models that went into its development, was built for this purpose. The simulation model operationalizes constructs from the dominant view of coordination in crisis response, using an agent-based representation that enables experimenting with both top-down mediated coordination mechanisms as well as bottom-up mutually adjusted coordination mechanisms for a crisis response organization in a specific crisis scenario. Experimenting with this simulation model provides theoretical insight about coordination and about the supporting role that ICT has.

The contribution.

Crisis response is critical for society in general, but more specifically for health authorities, fire departments, municipalities, large industrial complexes, or national security boards, among others. Such organizations are constantly facing the risk of a crisis for which they need to activate *ad hoc* networks of people or agencies to handle the situation (to prevent escalation, mitigate the impact and recover). In today's world, climatic disasters, terrorist attacks and pandemics grasp public attention; and in the event of such a crisis, leadership and coordination are required even across international borders. For example, potential pandemics involve authorities at an international (i.e. World Health Organization), national (i.e. Health Ministry) and regional (i.e. hospital management) level, but also need the compromise of political leaders and media in order to put potential victims on alert. If the virus spreads and victims grow in number, other services may need to act, such as ambulance services, detoxifying units, and even airport authorities and security personnel. The speed and accuracy with which these services become aware and react is critical for the emergency to be contained or controlled; and this depends on them being coordinated.

The domain.

Large crises or disasters require intensive communication, coordination and immediate response to a changing environment (Chen & Decker, 2005). Accordingly, an effective response cannot be achieved unless coordination is in place (Chen, Sharman, Rao & Upadhyaya, 2007). However, coordination continues to be the key hidden problem in crisis response that has been largely ignored (Turoff, Chumer, van de Walle, & Yao, 2004). Moreover, academic research on this problem is still scarce (Chen, Sharman, Rao, & Upadhyaya, 2008). This opportunity offers a challenging environment in which to study the dynamics of multi-organizational coordination (Chen & Decker, 2004). In addition, the organizational structure of a crisis response effort interacts with the information and ICT structure to coordinate the response activities (Leidner, Pan, & Pan, 2009). However, there is a gap between the possibilities that ICT offers and the support it delivers. In this chapter we look at the challenges in coordinating a crisis response and the existing ICT that supports it. This leads to research questions and to the approach used to answer them.

The opportunity.

1.2 Vignette: An Example of a Crisis

The following is an example of a crisis requiring coordination across multiple levels and disciplines. Although there are plans and lines of authority to handle the incident, the situation and the response organization are constantly changing, requiring adaptation and flexibility. The incident starts with an excavator working on a minor road, at the edge of a small municipality in The Netherlands. Suddenly, a truck carrying flammable liquid crashes onto the excavator rolling over to the side of the road (see Figure 1-1). A routine response to a traffic accident starts with fire, police and medical services. On arrival, the Officers on Duty (*Officieren van Dienst*, OvD) meet in a consultation zone – or *motorkapoverleg*, literally referring to a rendezvous on the hood of a car that is often used as a make do table – to assess the situation and determine the scale of the incident.

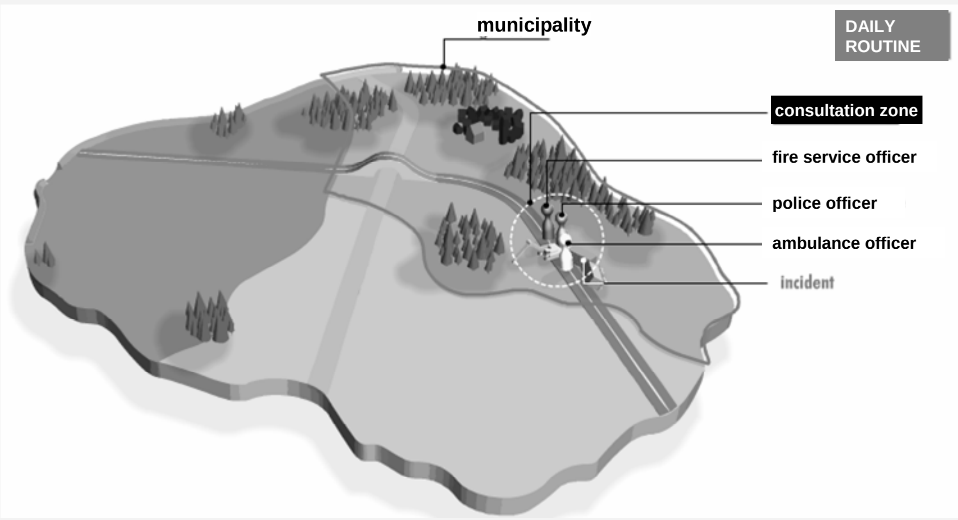

Figure 1-1 Grip level 0, adapted from (Ministerie van BZK, 2007)

Crisis response in The Netherlands is organized according to the Coordinated Regional Incident Management Procedure (*Gecoördineerde Regionale Incidentenbestrijdings-procedure*, or GRIP) (Trijselaar, 2006). This procedure defines GRIP levels which describe the organizational structure and tasks that should be executed once an incident requires a multidisciplinary response. It starts at GRIP 1 when the incident can be locally managed by an Incident Command (*Commando Plaats Incident*, or CoPI) and its corresponding CoPI Team (*CommandoTeam Plaats Incident*, or CTPI). If the incident escalates and another municipality may be affected, the GRIP scales up to level 2 and a Regional Operational Team (*Regionaal Operationeel Team*, RegOT) is setup, which follows a similar structure and dynamic than the CoPI, but on a regional level. GRIP 3 should be declared when there is a serious threat to the population, and GRIP 4 when the incident geographically spreads and involves more than one municipality.

A schema of the basic organizational structure is presented in Figure 1-2. In parenthesis, a number indicates the GRIP level were the organizational units enters the response structure. Any emergency starts with the field units; then, the CoPI team is established in GRIP 1; after that, a RegOT and Action Centers are setup in GRIP 2. After GRIP 3 Mayors are involved (not just informed). When GRIP 4 is declared, a Coordinating Mayor is designated and there is provincial oversight over the response.

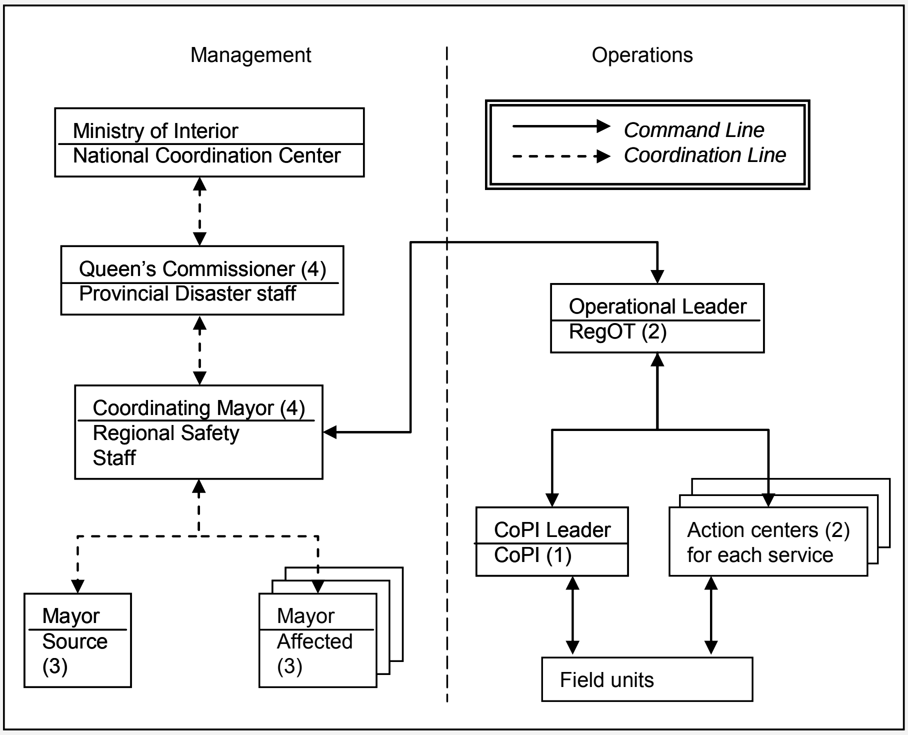

Figure 1-2 Schema of the GRIP levels, adapted from (Trijselaar, 2006)

In our crisis example, the truck has caught fire, requiring multidisciplinary coordination between response agencies at a local level. Thus, the OvDs in the consultation zone declare a GRIP 1 scale for the emergency (Figure 1-3).

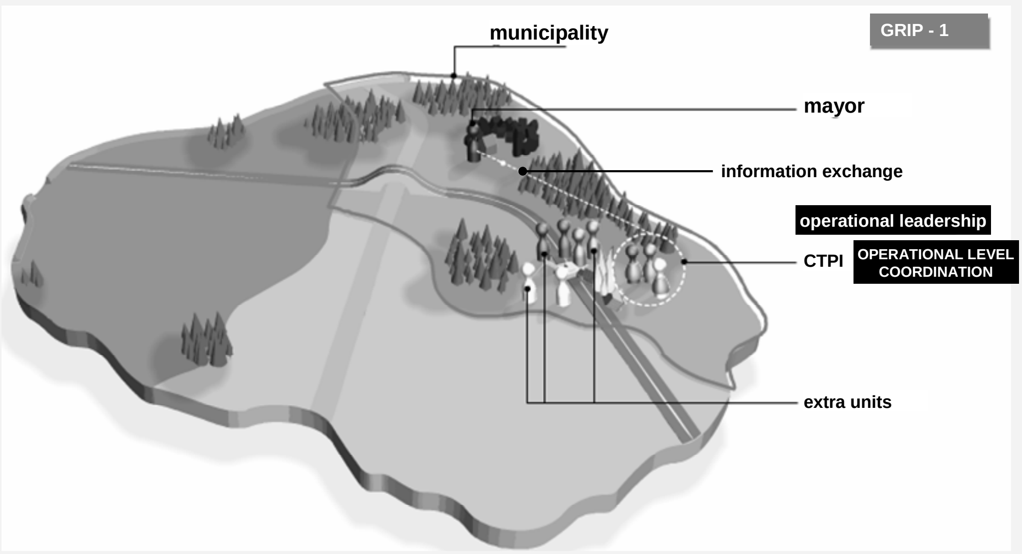

Figure 1-3 GRIP level 1, adapted from (Ministerie van BZK, 2007)

At GRIP 1, the CTPI is set up and coordination takes place without a formal commander, although by default the Fire Officer (*OvD-Brandweer*, or OvD-B) acts as CoPI Leader and the Mayor is informed of the situation. But because the fire has now spread to the border of the municipality, the incident becomes a regional concern and the CTPI decides to scale up to GRIP 2 (see Figure 1-4).

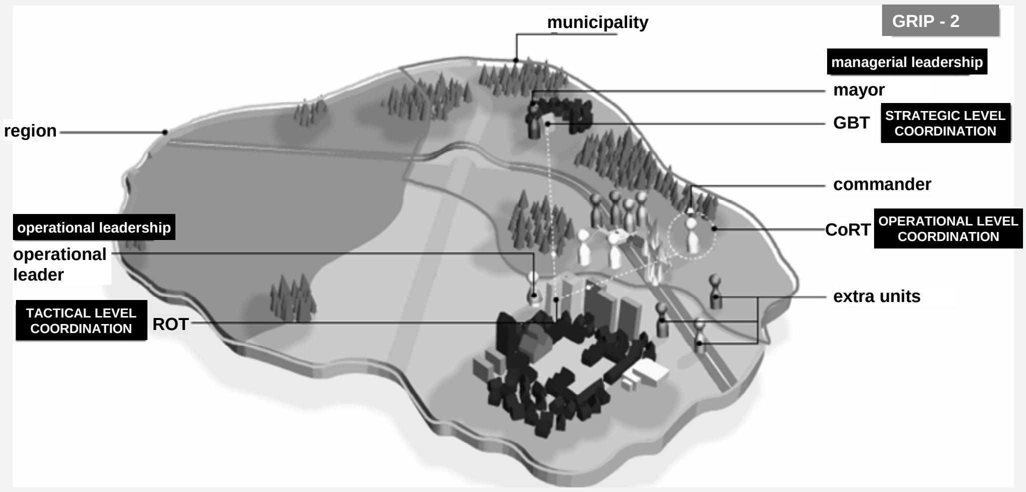

Figure 1-4 GRIP level 2, adapted from (Ministerie van BZK, 2007)

The CTPI is transformed into a Regional Incident Command (*Commando Rampterrein*, CoRT). The corresponding RegOT (see Figure 1-2) is established with its leader, the Regional Fire Officer (*Commandant van Dienst*, CvD), becoming the Operational Leader (OL) of the response. Managerial coordination is advised by a Municipal Policy Team (*Gemeentelijk Beleidsteam*, GBT) and the Provincial authorities are informed. Despite the fact that the response is underway, the fire has continued to spread into a region where a large town is threatened. The incident is scaled up to GRIP 3 (Figure 1-5).

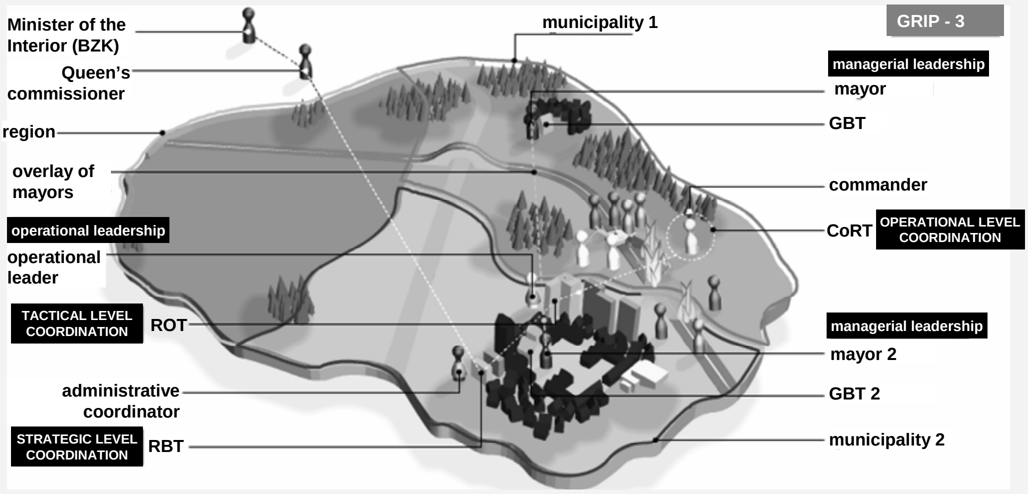

Figure 1-5 GRIP level 3, adapted from (Ministerie van BZK, 2007)

GRIP 3 implies regional managerial coordination, changing the GBT into a Regional Management Team (*Regionaal Beleidsteam*, or RBT) and the Mayors from the two municipalities must now work together, with the first acting as Coordinating Mayor (see Figure 1-2). The fire is still going strong and is now inside the two regions and has reached a chemical plant, so the incident is scaled up to GRIP 4, as seen in Figure 1-6.

GRIP 4 is very serious (the original accident seems simple now). There is a fire at a chemical plant emitting toxic fumes and difficult to contain. The incident is now of national concern and requires a Provincial Coordination Center (PCC) and a National Coordination Center (NCC) strategically led by the Ministry of the Interior, though operational leadership still remains at the regional level. There are victims and a large population under threat. Decision-making, action and coordination need to occur at the operational, tactical and strategic levels, involving multiple disciplines (and external advisers) in an organization that just a couple of hours ago did not exist.

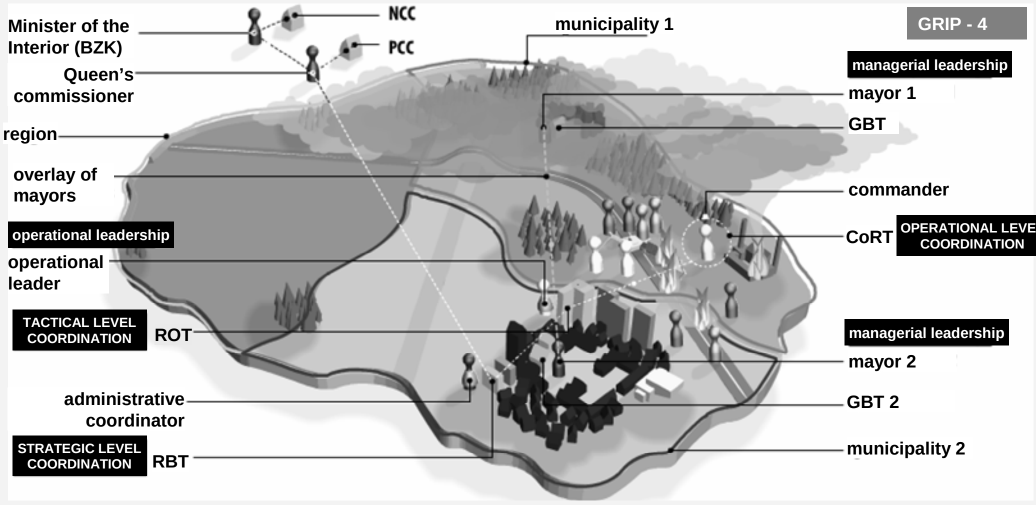

Figure 1-6 GRIP level 4, adapted from (Ministerie van BZK, 2007)

1.3 Coordination Issues in Crisis Response

Good coordination is often invisible, sometimes we only notice it when it is lacking (Malone & Crowston, 1990). This section points out some of the most important issues surrounding coordination (or rather the lack of it) in crisis response. During a crisis or emergency, many of the logistical problems are not caused by lack of resources, but by failure to coordinate their distribution (Chan, Killeen, Griswold, & Lenert, 2004). Conversely, successful operations are often attributed to effective inter-agency coordination (Smith & Dowell, 2000). Coordination is thus a key requirement for successful crisis response operations. However, achieving coordination is especially challenging in this domain, because the difficulties in achieving coordinated action are endemic to the nature of an affected emergency area (Comfort, Ko, & Zagorecki, 2004).

Coordination challenges are endemic to a crisis,

Often, crises require a response from multiple agencies, which may include regular emergency professionals such as medical, police and fire services, but also expert agencies for dealing with hazardous materials or epidemics. Other agencies involved in the response may be specific to the incident location, jurisdiction or context, such as the municipality, representatives from industrial complexes, or local safety and security personnel. In addition, whether through the involvement of civilians as responders during the first few minutes, or through long-lasting organizations, volunteers can also play a role. This creates an *ad hoc* response organization with members that may not have worked together before (Dawes, Cresswell, & Cahan, 2004; Smith & Dowell, 2000). As a result, crisis response is challenged by multi-authority, massive people involvement and conflicts of interest (Chen *et al.*, 2008). This often means an absence of an adequate consistent shared mental model (Smith & Dowell, 2000) hampering the ability to effectively coordinate behavior from the top-down (Bigley & Roberts, 2001).

especially one of a multi-disciplinary nature.

The resulting heterogeneity in response agencies introduces barriers in communication, in information sharing, in decision-making and in operations (Chen *et al.*, 2007). In addition, each response agency operates with different assumptions and the lack of a clear authority often leads to mistakes (Turoff *et al.*, 2004). As expected, there will be minimal common structures and procedures, especially when the incident crosses borders, creating massive coordination problems (Harrald, 2006). This is exacerbated by the large range of data from different sources and in different formats, such as: web, satellite, pictures, audio and news articles (Adam *et al.*, 2007; Bloodsworth & Greenwood, 2005; Bui & Lee, 1999). Technically, heterogeneity is based on different hardware, software and communication systems, but semantically there will also be disagreement on definition, meaning, interpretation, transformation or intended use of data.

Coordination issues include: heterogeneity,

Consequently, there is a tight relationship between coordination and information management. During a crisis, a lack of adequate information is the number one cause of delay preventing early situation awareness, among others (Chen *et al.*, 2007; Comfort, Ko *et al.*, 2004; Harrald, 2006). A high demand for information requires it to be updated constantly and scaled to different levels of the organization (Chen *et al.*, 2008; Comfort, Dunn *et al.*, 2004). This implies rapid search, exchange and absorption of accurate information regarding sudden, damaging events (Comfort, Dunn *et al.*, 2004; Petrescu-Prahovaz & Butts, 2005). But while relevant, accurate, timely and accessible data is critical, unfortunately these tend to be absent qualities (Dawes *et al.*, 2004). It is also likely that the information exchanged is of limited quantity and quality or incomplete and contradictory (Chen *et al.*, 2007). This can lead to misunderstanding between the participating response agencies (Steinberg & Cruz, 2004). To make things more difficult, information sharing and organization can be hampered by technical and communication barriers, as well as politics, regulations, security and privacy (Kim, Sharman, Rao, & Upadhyaya, 2006). For example, the natural tendency to focus on the physical response, de-emphasizes data collection and communication (Heath, 1998). Also, it is quite possible that communication channels become impaired during a crisis (Chen *et al.*, 2008; Chen & Decker, 2005).

information management,

Even if there are information management systems in place, a constraint we can not do away with is the cognitive limitation of humans interacting with the system and each other. Processing crisis information is limited by human cognitive capacity – the more information, the less the capacity to absorb it (Comfort, Dunn *et al.*, 2004). Information overload may result from receiving too much information and is related to: cognitive, sensory, communication or knowledge overload (Eppler & Mengis, 2004). The information related to an incident is mostly missing when an incident occurs. There may be historical data, simulation data, lessons learned, contingency plans, predictions and sensor information for early warning, but these will not be enough for making complete sense of the incident once it occurs. However, this initial lack of information quickly turns into overload, because when a large-scale disaster happens, a great deal of information occurs in a short time (Atoji, Koiso, & Nishida, 2000). The fact that the response is full of uncertainty means that more information will have to be processed for decision-making, while at the same time, the pressure of acting quickly places additional cognitive constraints on decision-makers.

information overload,

The lack of relevant information (or the excess of potentially irrelevant information), together with sudden and unexpected events, creates a permanent state of uncertainty during a crisis, which poses a great challenge for coordination (Chen *et al.*, 2007; Chen *et al.*, 2008; Chen & Decker, 2005). Under these circumstances, exact actions and responsibilities cannot be predetermined (Turoff *et al.*, 2004). Even roles cannot be predetermined as they depend on the situation (Petrescu-Prahovaz & Butts, 2005). On top of this, the relationship between the demand posed by the crisis and the capacity of the response organization is continuously changing (Comfort, Ko *et al.*, 2004). Two ways to deal with this uncertainty are improvisation and flexibility, but both create additional challenges.

uncertainty,

During a crisis, it is often the case that response plans become quickly outdated (Bloodsworth & Greenwood, 2005; Mendonça, Beroggi, & Wallace, 2001). In the preparation phase, plans "should be practiced, examined regularly for improvement, and updated as materials, technology, and personnel change" (Steinberg & Cruz, 2004). During the response phase, plans should adapt by reconfiguring functional units, reassigning locations or redefining interconnections (Ulieru & Unland, 2004). But because of the aforementioned uncertainty, plan adaptation can seldom be proactive. Thus, achieving coordination through plans becomes improbable and the organization needs to become flexible and adapt through coordination by feedback, based on the transmission of new information to facilitate mutual adjustment between responders and agencies (Dynes & Aguirre, 1979).

adaptation,

Improvisation is another mechanism, besides adjustment through feedback, to adapt to unexpected events when the response plan cannot be reconfigured or an alternative plan is not available (Harrald, 2006; Mendonça *et al.*, 2001). If the situation does not fit the original design, results may be completely wrong so people need to be encouraged to allow improvisation and creativity (Turoff *et al.*, 2004). When a multi-faceted unpredictable event arrives, plans can be combined in unexpected ways calling for a creative improvised response which both addresses the contingency and is viable in the available time (Mendonça *et al.*, 2001). However, one of the issues with this kind of pragmatic and *ad hoc* response is that, rather than depending on the plans or standards (over which there is a certain amount of control), it depends (too much) on personalities (Rietjens, Voordijk, & de Boer, 2007). In addition, while rapid variation and improvisation may lead to flexibility, this depends on how well such improvised behavior is integrated and coordinated, which in turn depends on the integrity of consistent operational representations (Bigley & Roberts, 2001).

improvi-sation,

There needs to be a trade-off between the flexibility needed to manage dynamic information and the order required to ensure that accurate information reaches the right people in a valid a format and in time (Comfort, Dunn *et al.*, 2004). This trade-off is also reflected in the organizational structure, where there is a tension between the command and control structure that many response agencies exhibit and the coordination and communication requirements of a crisis (Harrald, 2006). On one hand, fast decision-making comes from having a centralized authority in a command and control setting; on the other hand, effective response requires consultation and decentralization (Heath, 1998). As an example, during the SARS and Tsunami responses in Singapore, a flat centralized command and control structure did contribute to overall efficiency and

command and control,

interoperability (Leidner *et al.*, 2009). However, the specific context of Singapore (its size, its years of providing a single policy on ICT development and privacy) should not be generalized. Ultimately, there is a balancing act between command and control on one side and coordination and communication on the other.

time pressure,

It is one thing to be able to adapt and improvise freely, and quite another to do so under severe time constraints. Improving the time-to-action in crisis response is a critical requirement that has a great impact on potential human, monetary, infrastructural or operational losses. Increased time pressure and urgency is one of the key challenges to coordination in crisis response (Chen *et al.*, 2008; Heath, 1998). Decision-making is particularly time critical (Chen & Decker, 2005). In order to improve the time-to-action, there must be an awareness of all the potential delays that may occur and where coordination should become more intensive. Such delays include: initial selection of appropriate responders under fuzzy, incomplete and imprecise information; time used in preparing each response action; and time used to find information, make decisions and communicate them (Chen, Sharman, Rao, & Upadhyaya, 2005).

and insufficient resources.

Under the stress of a serious crisis, there will very likely be severe resource shortage, creating problems for coordination (Chen *et al.*, 2008). In addition, the crisis itself may disrupt the infrastructure support (*ibid.*). These resource and infrastructure limitations and vulnerabilities may result in hampering the communication capacity, the reliability and security, the coordination with national capabilities, and the capacity for early detection and response (Kim *et al.*, 2006). However, even when resources are available in excess, many organizations and individuals fail to find adequate support or services in different stages of the emergency response (e.g. first respondents concentrate on urgent demands, while the recovery period poses long-term needs) (Comfort, Ko *et al.*, 2004).

The above issues are influenced by tradeoffs…

All of the above considerations for coordinating crisis response are exacerbated by the fact that they cannot be ascribed to a single organization or tackled through a single approach. Regardless of how prepared, trained and coordinated response agencies are on their day to day operations, the crisis organization (especially for large-scale emergencies) is altogether a different structure (Heath, 1998). Once it is in place, there will be a problem in coordinating the interaction between the structure of this emerging crisis management system and the techniques of individual and team decision-making (Smith & Dowell, 2000). The barriers to coordination lie not so much in the establishment of a common goal (since saving lives and preventing losses are ultimately shared objectives) but rather in the structure of organizations seeking a common approach (Comfort, Dunn *et al.*, 2004). This results in a need for coupling the closed view on preparedness, structured planning and organization, with the open view on flexibility, adaptation and improvisation (Harrald, 2006). As a result, most coordination issues create tradeoffs in terms of requirements and goals, i.e. between individual and group behavior, between control and flexibility, between making faster decisions or seeking more complete information, between planning and improvising, and so forth.

An important aspect of the tradeoffs present in crisis response is emergent behavior, which has been studied in crisis response for a long time (Dynes & Aguirre, 1979; Quarantelli, 1989) and continues to be a subject of research

(Petrescu-Prahovaz & Butts, 2005; Voorhees, 2008). In terms of coordination, emergence means that it is not planned or a result of organizational designs, but rather the result of "local" or lower-level interactions that result in "global" or higher-level coordinated action. Emergent coordination can result out of individual response agents interacting autonomously, but this interaction is not sufficient in itself to explain or account for the behavior of the whole system. While emergence occurs from the bottom-up, it is also part of a specific structure of interaction, which is neither at the level of the system as a whole, nor at the level of the entities: it is constitutive of both (Dessalles, Ferber, & Phan, 2008). In other words, emergence implies both upwards and downwards causation, which is why coordination of an emergent kind is neither a result of purely bottom-up mutual adjustment through feedback, nor top-down control through standards or hierarchy. Even if emergent coordination is a global property resulting from low-level interactions or rules, it is also the case that such rules and interactions are only possible within a particular structure imposed by the system as a whole.

and by emergence.

Furthermore, during a crisis, emergent coordination can end up having the same characteristics as structured hierarchical coordination, as the World Trade Center disaster of 2001 showed. One study of social networks of communication showed that *ad hoc* emergent communication structures between non-professional responders were similar to those of a hierarchically arranged professional response organization (Petrescu-Prahovaz & Butts, 2005). This suggests that coordination can result equally through highly organized and well-trained hierarchies, as well as from autonomous interaction adjusted until structure emerges. The question is whether this kind of coordination can be more effective and under which circumstances. Also, there are risks involved: there is no guarantee that structure will indeed emerge (quickly enough) and there is the chance that it will result in maladaptive structures. Thus, there is still a need to improve our understanding of how emergent coordination occurs in order to be better prepared to enable it when necessary or keep it in check when it is leading in the wrong direction.

To contribute to dealing with the above coordination-related issues, various information and communication technology (ICT) is used in crisis response. With this technological support, it is possible to support communications, information processing and exchange, decision making, dynamic plan adjustment, training and standardization, among others. This is the subject of the next section.

1.4 ICT-supported Crisis Response

Crisis response information systems can be thought of as composed of ICT, together with the institutional arrangements and situated uses of the technology by crisis professionals and other users. However, in spite of the critical role of information and the wide variety of technologies available for managing it during an emergency, information systems often appear as a tangential theme in crisis research (Leidner *et al.*, 2009). Nonetheless, there is increased recognition that ICT use can improve inter-organizational communication and coordination during crises (Kapucu, 2006). The ICT that contributes to improving coordination in crisis response is varied and depends on what it is that needs to be coordinated.

ICT can support crisis response coordination.

As an illustration, according to Chen *et al.* (2007), information coordination requires information management through collection and infusion, correlation and analysis, and sharing and dissemination. Resource coordination requires categorization and standardization, allocation control, and monitoring and tracking. Workflow coordination requires planning and scheduling, task assignment, escalation and de-escalation, progress monitoring, and performance monitoring. Decision coordination requires a pre-planning archive, a reference and knowledge base, group decision support, knowledge elicitation, conflict solving mechanisms, and inter-personal communication.

Crisis response information systems have…

But since the ICT alone does not provide the full support implied by a crisis response information system, the development and implementation of ICT needs to be part of a wider effort. In an early paper on the subject, Housel *et al.* (1986) proposed the following process for developing information systems for crisis management: (1) acknowledge the inevitability of crises; (2) identify critical areas of vulnerability; (3) identify and classify potential types of crises; (4) develop crisis management contingency plans; (5) develop information systems for crisis management (communication network analysis, change management method, and hardware and software selection for predictable and less predictable events, including early warning systems); (6) conduct crisis drills and exercises; and (7) use crisis information technologies for day-to-day situations.

Several scholars have continued to provide requirements or design premises to be followed when developing information systems for crisis response. We refer to them as guidelines and summarize some of them in Table 1-1.

existing guidelines.

Table 1-1 Guidelines for crisis response information systems

Modeling, simulation, training and day-to day use should be enabled in order to guarantee support in the event of a crisis.	(Housel *et al.*, 1986; Jefferson, 2006; Turoff *et al.*, 2004)
Information collections, analysis and free exchange should be supported. Data should be properly identified, valid, timely, and focused on the incident.	(Chen *et al.*, 2005; Jefferson, 2006; Kim *et al.*, 2007; Turoff *et al.*, 2004)
There should be a directory and/or database of first responders, resources, and system data, enabling collaboration, tracking, monitoring and identification. This should be partly available as an online community of experts, including expertise and competencies.	(Chen *et al.*, 2005; Jefferson, 2006; Turoff *et al.*, 2004)
Information and knowledge management systems should be in place with task related information, collective memory and lessons learned.	(Chen *et al.*, 2005; Jefferson, 2006; Turoff *et al.*, 2004)
Communication should be open, multi-directional and integrated to allow obtaining and maintaining situational awareness as well as alerting and warning the public. Interoperability can be partially achieved through standardization of formats and systems.	(Chen *et al.*, 2005; Dawes *et al.*, 2004; Jefferson, 2006; Kim *et al.*, 2007; Turoff *et al.*, 2004)

Table 1-1 Guidelines for crisis response information systems (contd.)

General features should include: decision-making support; multimedia support (including geographic information), security support, fault tolerance, redundancy, modularity and scalability.	(Chen *et al.*, 2005)
Other considerations: treating exceptions as rules; supporting authority, responsibility and accountability; supporting and encouraging the psychological and social needs of the response team; and preventing excessive regulation on security and privacy.	(Kim *et al.*, 2007; Turoff *et al.*, 2004)

ICT for crisis response includes:

In order to follow these guidelines, there is a wide array of ICT already at our disposal, including: radio communication, mobile phones, satellite and wireless capabilities to backup congested or destroyed land or radio lines, geographic positioning systems, miniature smart devices, mobile incident support systems, and geographic information systems (GIS) (Chan *et al.*, 2004; Dawes *et al.*, 2004; Landgren, 2007). The rest of this section briefly introduces some of the ICT systems that are currently available for supporting crisis response.

workflow technology,

Workflows and workflow management systems (WfMS) have for many years been an important aspect of coordination of people and software, including in crisis response (Bui & Tan, 2007). For example, they can support automation, visualization and simulation, seamless tool integration, monitoring, alarms, collaboration support, and decision support (Mak, Mallard, Bui, & Au, 1999). A workflow is the coordinated execution of multiple tasks or activities, which follow a well-established procedure and rely on humans and computers to carry out each task (Marinescu, 2002: Preface). Workflow technology is thus seen as the leading process-oriented coordination tool, initially only suitable for routine, repetitive processes with a fully defined model (Marjanovic, 2005). Current WfMS focus on control and this normally works against flexibility (Narendra, 2004). Some flexibility can be achieved by adapting the workflow in execution time or by selecting between a pre-existing set of workflows at build-time (Nurcan & Edme, 2005). Nonetheless, WfMS are still for the most part not able to cope with ill-defined processes, exceptions or failures, possibly threatening creativity and innovation (Müller, Greiner, & Rahm, 2004; Narendra, 2004; Nurcan & Edme, 2005). This makes the use of workflow technology limited for crisis response.

agent technology,

Agent technology is one of the dominant trends in crisis response ICTs (van de Walle & Turoff, 2007). An agent can be seen as a software program with autonomy, mobility and intelligence, which interacts with other agents either as an independent service provider/consumer or represents a real-life agent and acts on its behalf. This typically requires an important coordination effort in itself, making multi-agent systems (MAS) both a strong domain for studying and testing coordination mechanisms, as well as a source of coordination support for systems and people. Early on, workflow-style solutions were devised to coordinate agent task schedules (Liu & Sycara, 1998), but suffered from the same lack of flexibility discussed above for WfMS. A more flexible solution to coordination is globalized partial global planning (GPGP), based on scheduling of agent tasks while supporting distribution and heterogeneity (Decker & Lesser, 1998). This approach has been tested for crisis response through simulation (Chen & Decker, 2005). One example application uses partial global sharing of schedule information and synchronization of coordination decisions for providing decision-support to first response teams (Wagner, Phelps, Guralnik, & VanRiper, 2006). Teamwork algorithms are another approach for agent coordination where agents have a detailed model of each other which they use to reason about actions to achieve common goals; this approach has been used to simulate teams of ambulances during a crisis (Xu, Liao *et al.*, 2006). Another MAS application supports an adaptive infrastructure, which can enable adaptation of agents to highly unpredictable situations, as those encountered in emergency response (Ulieru, 2005; Ulieru & Unland, 2004). A final example is an environmental emergency management framework which allows agents to achieve a common goal-preparedness for the emergency response and an agent-based resource discovery architecture to search for the relevant resources over the Internet (Liu, 2004).

decision support systems,

Decision support systems (DSS) can be used in crisis response to counteract time constraints and stress by providing data analysis, event recognition and prediction, intelligent checklists, and information prioritization, through knowledge, data mining, data aggregation, collaboration support and multi-criteria decision analysis (Andrienko & Andrienko, 2005). This can contribute to better informed improvisation (Mendonça *et al.*, 2001). DSS can also be applied to supporting preparedness and mitigation, role multiplicity, planning and analysis, and emergency management (van de Walle & Turoff, 2008). Some DSS can integrate geographic information systems (GIS) to provide monitoring, risk assessment and simulation services for multidisciplinary crisis management (Keramitsoglou, Kiranoudis, Sarimvels, & Sifakis, 2004). When combined with agent technology, a DSS can use agents as digital assistants for generating crisis action procedures (Bui & Lee, 1999). Similarly, the agents can make use of an ontology to provide intelligence to emergency managers (Gadomski, Bologna, di Costanzo, Perini, & Schaerf, 2001). The agents can also focus on information management, leading to better coordination during a crisis (Zhu *et al.*, 2007).

information management systems,

Other information management systems contribute to gathering, filtering and fusing crisis-related information. An example of this is a content and user-based information filtering of emergency related information (Atoji *et al.*, 2000). Another example is data mining using web services for event prediction and alarm disambiguation and also for checking consistency between different response agencies rules and policies (Adam *et al.*, 2007). In most cases, such support is enabled with intelligent agents, which can for instance be automated to gather news feeds from the Web and turn them into a knowledge base for answering questions during the crisis (Goh & Fung, 2005). They can also be configured as a distributed perception network for fusing heterogeneous information to contribute to situation awareness (Pavlin, de Oude, & Nunnink, 2005). Such support is related to decision-support, as in the case of a multi-agent system designed to monitor news feeds and emergency service reports to determine if an incident has taken place (and its nature); the system also regularly collects data from local hospitals to determine current capacity and to match casualties to capabilities through a web-based schedule (Bloodsworth & Greenwood, 2005).

The ability of geographic information technologies (GIT) to provide detailed, multilayered, visual incident-related data is an indispensable resource for emergency responders (Harrison, Pardo, Gil-Garcia, Thompson, & Juraga, 2007). According to Harrison *et al.*, general appreciation of GIT changed dramatically as a result of the response to the World Trade Center attacks of 2001. GIT allowed responders to construct innovative technological tools enabling support that would not have been possible otherwise. Geographic information systems (GIS) are one of the most pervasive technologies for crisis response and can provide views on the affected terrain for training, damage assessment or planning (Johnson, 2005). Enabled with 3D capabilities, they can contribute to quick emergency response in micro-spatial environments (Kwan & Lee, 2005). They can also be implemented with agents to support multi-level emergency operation centers (Cai *et al.*, 2005).

geographic information technology,

Knowledge management systems can be used to record and disseminate lessons learned from exercises and real responses through the web (Jenvald, Morin, & Kincaid, 2001). They can also be deployed to support emergent knowledge during a crisis as it evolves (Kakihara & Sørensen, 2002). Another application can support emergency preparedness by maintaining common "wikis" that different agencies can share (Raman, Ryan, & Olfman, 2006). When aligned with crisis response procedures, knowledge management can support detection, preparation, containment, recovery and learning (Wang & Belardo, 2005).

knowledge management systems,

Although simulation and gaming in crisis response are often used for training purposes, they can also be used for planning, designing decision-support systems, technology assessment, testing of contingency plans and practicing coordination (Kleiboer, 1997). Micro-scale simulation can be used for assessing ICT before implementation for actual crisis response (Robinson & Brown, 2005). Agent-based simulation can be coupled to augmented reality also for testing ICT tools prior to use in disaster response (Massaguer, Balasubramanian, Mehrotra, & Venkatasubramanian, 2006). And finally, the RoboCup Rescue platform for agent-based simulation can be used to test task allocation mechanisms for rescue operations (Suárez, Collins, & López, 2005).

simulation and gaming,

Many of the weaknesses of coordination technologies derive from the fact that they have evolved separately and are not integrated; truly effective coordination requires an integrated approach wherein dependencies across all the dimensions of cooperative work distribution are modeled and managed in a single computational framework (Klein, 1998). Given the diversity of crisis response technology, some systems are dedicated to providing such as framework in the form of a common or integrated crisis management system. Such a system may include global information networks with real-time information sensing, GIS, knowledge-based information filtering, teleconferencing, computer assisted logistics, just in time (JIT) support, group decision support, and computer assisted voting (Bui, Cho, Sankaran, & Sovereign, 2000).

and integrated systems.

Despite the availability of the above technologies, Katrina and the Indian Ocean Tsunami resulted in the breakdown of coordination processes and even advanced ICT did not seem to contribute to faster relief (van de Walle & Turoff, 2007). In the US and Sri Lanka, people turned to web sites created by volunteers rather than those provided by the government or professional agencies.

But ICT is sometimes not used…

In addition to volunteer-based web sites, new emerging technologies for crisis response include: citizen led on-line forums, public warning systems (including radio, TV and SMS) and social networking applications (Shneiderman & Preece, 2007). Mobile and wireless technologies are also increasingly used to support emergency services for rural areas (Horan & Schooley, 2005), to enable mobile devices to act as a single system during a crisis to manage distributed resources (Sapaty, Sugisaka, Finkelstein, Delgado-Frias, & Mirenkov, 2007), or configured as a sophisticated intelligent mobile crisis response systems to support communication and coordination (Yuan & Detlor, 2005). This results in the need to make sense of the different technologies and mixing and matching them depending on the context (van de Walle & Turoff, 2007).

The adoption of these new technologies is also an indication that emergent coordination is increasingly possible with the support of ICT. Rather than using fixed, closed systems, it is now possible to use decentralized, open, and in many cases cheaper and easily available alternatives which are embraced during the crisis. Some of them (such as *ad hoc* wireless networks or social networking applications) are even setup while the emergency is still in progress. This research considers the relationship between ICT and coordination, placing special emphasis on emergence as a possible way to improve the efficiency and effectiveness of the response. Having established the background, the last two sections in this chapter formulate the resulting research objectives and questions and the research approach that is used to tackle them.

1.5 Research Objective and Questions

The previous problem situation leads to…

From the previous sections, certain key elements that create a problem situation worth researching can be identified. The issues related to coordination become exacerbated during a multidisciplinary crisis response. An *ad hoc* organization of responders displays heterogeneity, information management difficulties and uncertainty, under resource limitations. In addition, the need to be flexible, to allow improvisation and to account for emergence is set against the command and control structure of response agencies and the need for some centralized decision-making. ICT can be used to deal with these challenges, either by supporting resilient and open communication and providing information management services, or by providing workflow, decision or knowledge management support. Additional technology is used in supporting responders and crisis managers before, during and after the crisis: multi-agent systems, geographic information systems or simulation and gaming. Although some attempts have been made to provide an integrated infrastructure or overarching system to configure these different technologies, during actual emergencies much of the available ICT support is not used (properly) and new (mostly web-based) technologies are emerging. This creates a gap between the possibilities and realities of ICT support during crisis response. As a consequence, coordination is still, despite many technological advances, an unresolved issue which has not received sufficient attention, despite being pointed out as key challenge to effective and efficient crisis response. As such, it creates an opportunity for improvement that is the basis for the objective and questions behind this research.

In order to improve ICT-supported coordination in crisis response, a clear understanding of coordination in this domain is necessary. Some of the coordination challenges conflict with each other due to the vary nature of a crisis. The response is expected to be quick and effective, while at the same time careful and accountable. A structured, well-trained organization with clear lines of authority should provide the leadership and accountability that an emergency requires; while at the same time, the network of responders needs to be flexible enough to adapt and embrace creative and improvised actions for unknown situations. An improved understanding of coordination during crisis response is required both to distinguish it from coordination during more regular operations and from coordination within a clearly bounded organization, whose structure is subject to top-down design and dedicated ICT support. This also implies an improved understanding of the role that ICT plays to support coordination under these special conditions. Ultimately, this can contribute to saving lives and minimizing loss once a crisis is underway. The research objective is thus:

RO. To provide design constructs, models, methods and an instantiation for extending the current understanding of coordination in crisis response.

a research objective…

In order to achieve this objective, this research focuses on the following research questions:

RQ1. How can the current understanding of coordination in crisis response be extended to account for emergent coordination?

RQ2. How does coordination based on centralized command and control compare to decentralized or emergent coordination in crisis response?

and research questions.

Answering those two questions should also lead to answering a third question regarding the role of ICT:

RQ3. How does an extended understanding of coordination in crisis response and of its alternative configurations contribute to bridging the gap between the possibilities and realities of ICT support during a crisis?

In the next section, the research approach for tackling the previous research questions is presented along with the outline of the rest of this thesis.

1.6 Research Approach and Outline

Before outlining the research approach, some background on the spectrum of research choices in the field of information systems is needed.

Research in information systems

This research is conceived within the field of information systems (IS), as a problem of organizationally situated ICT around the issue of coordination. However, IS has many different interpretations probably because the field itself is broad and multidimensional, as noted by Mingers (2001). Most researchers see IS as a socio-technical field, e.g. Hirschheim (1992), and many disciplines (including management, sociology, computer science, and psychology) are cited as informing

Research in IS can be composed of:

its research and practice (Checkland & Holwell, 1998). This socio-technical understanding, has given rise to multiple approaches to IS research, which can be classified in terms of the underlying philosophy, the strategy and the instruments.

research philosophy

The research philosophy provides the ideological basis of a methodology. Typically, it is seen as composed of ontology and epistemology, where ontology refers to the nature of being (Nandhakumar & Jones, 1997), and epistemology refers to the theory of knowledge, or how we acquire knowledge (Galliers, 1992).

(ontology

In information systems research, ontology can be based on realism or idealism. More specifically, *external realism* contends that reality exists independently of individuals and their representations of it (Hirschheim, 1992). *Internal realism* claims that reality is an intersubjective construction (Nandhakumar & Jones, 1997). *Critical realism* sees science as a process of explanation and enlightenment, rather than a derivation of predictive laws, and states that structures can only be identified indirectly through their effects (Dobson, 2002). On the other side of the spectrum, *idealism* can be viewed in the sense of the early platonic World of Ideas or linked to the German Idealism of Kant, Hegel and Fichte (Hirschheim, 1992). In its radical version, s*ubjective idealism* argues that reality is simply a construction of each individual (Nandhakumar & Jones, 1997).

and episte-mology),

Regarding epistemology, IS research can be classified as either positivist, interpretive or critical (Klein & Myers, 1999). *Positivism* emphasizes science as the only method conducing to truth; it claims that the social world can be described by law-like generalizations stemming from value-free facts; it aims at verifiability or falsification of theories; and it believes in causality, usually using a quantitative-empirical methodology (Hirschheim, 1992; Nandhakumar & Jones, 1997). *Interpretivism* argues that both the researcher and the human actors in the phenomenon under study interpret the situation; instead of generalization it aims at in-depth understanding (Chen & Hirschheim, 2004). According to the *critical approach*, there is no way to infer that a given law is true, no matter how many instances are analyzed; it denotes a critical process of inquiry seeking emancipatory social change through revealing hidden agendas, inequalities and manipulations (Cecez-Kecmanovic, 2001; Hirschheim, 1992).

strategy and

A research approach follows a given strategy grounded in a particular philosophy. We use the term strategy in the sense of an abstract methodology defined as: "an overall strategy of conceptualizing and conducting an inquiry, and constructing scientific knowledge… [which] refers not only to research methods or techniques (such as case study or interview), but also to the epistemological assumptions of methods and how they are linked to a particular theory" (Cecez-Kecmanovic, 2001). In information systems, increasing attention is being paid to the distinction between behavioral (or natural) science and design science as two different but complementary paradigms that can be used as research strategy (Hevner, March, Park, & Ram, 2004). While behavioral science aims at developing hypotheses and empirically justifying theories for explaining or predicting phenomena surrounding the analysis, design, implementation and use of IS; design science seeks to create artifacts that embody the ideas, practices, technical capabilities and products required to accomplish such analysis, design, implementation and use (Hevner & March, 2003).

Research instruments are understood here as the specific methods that are used to execute a particular research strategy, including:

instruments.

- Descriptive research is interpretive research studying literature or past research or events (Wynekoop & Russo, 1997).
- Lab experiments are studies within a designed, controlled environment, which typically include contrasting related variables (Chen & Hirschheim, 2004).
- Field inquiry may involve case studies, action research or ethnography. A case study investigates a contemporary phenomenon in real life, when boundary and context are not clearly evident or the prior knowledge of constructs and variables is inferior (Darke, Shanks, & Broadbent, 1998; Yin, 2003). Action research is concerned with actual planned change and production of theory in the process (Avison, Baskerville, & Myers, 2001). Ethnographic research requires a longer period of immersion in an unfamiliar situation, seeking to place the phenomena in a social and cultural context (Myers, 1999).
- Simulation as a method of inquiry, following Shannon (1998) and Sol (1982), can be defined as the process of designing a model of a concrete system and conducting experiments with this model in order to understand the behavior of said system and/or evaluating various strategies for its operation.
- There are also some additional research instruments that are usually contained within some of the above, but sometimes may be sufficient by themselves. Two common cases of such instruments are: 1) survey: gathering data through questionnaires (Chen & Hirschheim, 2004); and 2) interview: an interview is a data collection technique, which used qualitatively, seeks to describe the multiple realities of the subjects (Stake, 1995).

Research approach

According to Trauth (2001), not only the problem should dictate the choice of a research method, but also: the degree of uncertainty in the phenomenon, the researcher's theoretical lens and skills, and the institutional background.

Research choices are guided by:

The application domain poses some requirements and limitations on the research approach. Event though crisis research has for the most part the same methodological problems as any other social phenomena, it does have unique considerations: given the unpredictability of a crisis, it is impossible to know in advance when the next research opportunity will appear, posing restrictions on timely incident data collection; also, access to professional responders will become increasingly difficult (Drabek, 1970). With regards to survey studies, protecting quality, maintaining sample size, guaranteeing safety for researchers and obtaining clearance are especially challenging (Henderson *et al.*, 2009).

the application domain...

Considering the researcher's and institutional background, the engineering approach and the systems approach influence the research choices. Previous research has focused on problem-solving where multiple actors are involved in ill-structured situations. Whether explicitly or not, design science has oriented much of these research efforts, e.g. (Chin, 2007; van Houten, 2007). Through interventions or design of artifacts, research has been done for situations where a relevant contribution is sought using a strong technical component and informed

and the researcher/ institutional background.

by multiple disciplines. Case studies, e.g. (van Laere, 2003), and simulation studies, e.g. (Jacobs, 2005), have often been used to enable this design science strategy.

The research approach follows a…

In this research, design science is used as the overall strategy, supported with case studies and simulation and resting on the philosophical assumptions of design science with an interpretive epistemology and critical realist ontology. The rest of this section describes the approach in detail.

design science research strategy,

The genesis of design science lies in Herbert Simon's The Sciences of the Artificial (first published in 1969) in which he articulated the difference between natural science, concerned with how things are, and design science, concerned with how things ought to be, based on his understanding of design as problem solving (Simon, 1996, p. 114). Following Simon's tradition, design science was introduced in IS research by March and Smith (1995), who presented it as prescriptive research aimed at improving ICT performance, as opposed to natural science, corresponding to descriptive research aimed at understanding the nature of ICT. An important point was that IS research should actually integrate both perspectives, an argument that came back on Hevner *et al.* (2004), establishing design science research in information systems (DSRIS). A DSRIS contribution requires identifying a relevant organizational ICT problem, demonstrating that no solution exists, developing an ICT artifact that addresses this problem, rigorously evaluating the artifact, articulating the contribution to the ICT knowledge-base and to practice, and explaining the implications for ICT management and practice (March & Storey, 2008). A recent development of the initial design science framework presented in Hevner *et al.* (2004), decouples the previous goals into three distinct but interrelated research cycles, as shown in Figure 1-7.

This three-cycle view of design science suggests that relevance is attained through identification of requirements (or business needs) and field testing of an artifact within an environment, while rigor is achieved by appropriately grounding the research in existing foundations, methodologies and design theories and subsequently making contributions that add to the existing knowledge base. The design aspect is achieved through a *Design Cycle* in which the artifact must be built and evaluated thoroughly before "releasing it" to the *Relevance Cycle* and before the knowledge contribution is output into the *Rigor Cycle* (Hevner, 2007).

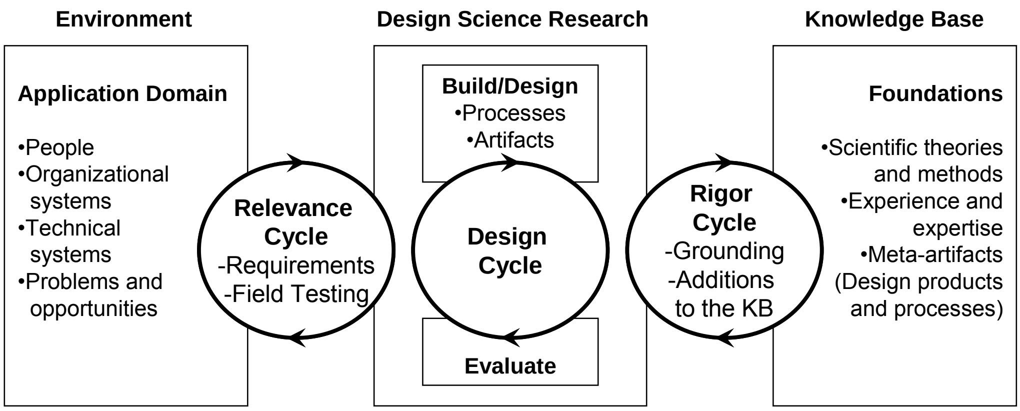

Figure 1-7 Design science research cycles, adapted from (Hevner, 2007)

Since design science is issue-driven, rather than theory-driven, e.g. (Klabbers, 2006), the *Relevance Cycle* guided the start of this research. An initial literature study of coordination in crisis response and of the role of ICT in supporting it provided an initial set of open issues shown earlier in this chapter. The *Rigor Cycle* then began with the articulation of a conceptual framework for studying coordination in practice and for identifying the limits of the knowledge-base that constitute an opportunity for theory extension, i.e. the information-processing view of coordination (Galbraith, 1973; Malone & Crowston, 1994). This led back to the *Relevance Cycle* for two case studies in which observation of crisis response exercises provided empirical content to the theoretical concepts and contributed to identifying context-dependent requirements. In order to get this in-depth and contextualized understanding of the relevant problem, the case study findings provided both the empirical content for the coordination issues and exemplified the role of ICT with real-world tools. The *Rigor Cycle* then continued, using emergence as an alternative/extension to the theory of coordination in crisis response. This included the study of emergent coordination in multi-agent systems and background notions of emergence in general. With these elements, the *Design Cycle* as such began.

using case studies and

A simulation study embodies this core *Design Cycle* for the following reasons: (1) simulation can be used for theory development/extension (Davis, Eisenhardt, & Bingham, 2007); (2) agent-based simulation in particular can be used to study emergent coordination (Macy & Willer, 2002); and (3) simulation is an adequate research method in crisis response were collecting data or directly implementing artifacts can be prohibitively expensive or risky (Kleiboer, 1997). For crisis response, simulations can be used to illustrate the patterns and pathologies of crisis decision making; they can create a great opportunity for getting acquainted with all aspects of crisis management; and they can help bridge the gap between theory and practice (Boin, Kofman-Bos, & Overdijk, 2004). Computer-based simulations can yield very cost effective and time efficient insight into emergency response organizations (Robinson & Brown, 2005). Agent-based simulation in particular can be used to develop domain-specific theory in the field of coordination (Dooley & Corman, 2002; Macy & Willer, 2002). Such theory development stems from a particular class of research question: it addresses the "what-if" of simulation in general, together with the interaction between local and global, micro and macro, individual and emergent behavior, and between structure and chaos (Davis *et al.*, 2007; Louie & Carley, 2008; Macy & Willer, 2002).

simulation.

The theoretical contribution (to extend the understanding of coordination in crisis response as the research questions mandate) is done both through the applicable knowledge base extracted from literature and through the operationalization of relevant concepts in the simulation model. The information-processing view of coordination is extended with notions from emergence, leading to new design constructs for modeling and simulating coordination in a particular crisis scenario. The simulation model embodies the designed artifact enabling experimentation with different coordination configurations. This contributes an artificial setting for systematically comparing and evaluating different coordination mechanisms, leading to the possibility of testing different hypothesis or design principles about coordination and the ICTs that can be used to support it during a crisis.

The results include an instantiated artifact…

This dual goal for DSRIS as producing both an artifact and a theoretical contribution deserves some discussion. March and Smith (1995) attach the activities of *Discovery* (generating or proposing scientific claims) and *Justification* (testing scientific claims for validity) to natural science and present them as separate from (but parallel to) the activities of *Building* (constructing an artifact for a specific purpose) and *Evaluation* (determining how well the artifact performs) attached to design science. In Hevner *et al.* (2004) the activities were merged into *Develop/Build* and *Justify/Evaluate*. This helps state the case in favor of having both relevance and rigor in ISR, but may also leave behind lack of clarity with regards to how theory development should be seen in DSRIS.

On one end of the spectrum, March and Smith (1995) explicitly exclude theory and theorizing from design science. On the other end, several authors contend that theory development should be an integral part of DSRIS (Kuechler & Vaishnavi, 2008; Markus, Majchrzak, & Gasser, 2002; Walls, Widmeyer, & El Sawy, 1992). Hevner *et al.* (2004) do not seem to take a stance either way, since they present a dual build/develop and evaluate/justify design cycle, potentially allowing for both artifact building and evaluation as well as theory development and justification. Since part of the objective of this research is to refine and extend the information-processing view of coordination within the domain of crisis response, the assumption is that DSRIS can be used for theory development.

and a theoretical contribution comprising…

When DSRIS is used for theory development, the next question is what kind of theory can result. Walls *et al.* (1992) speak of design theories, which are prescriptive theories about how to design information systems effectively and feasibly. Venable (2006) claims that design theories should be reduced to utility theories, which are predictive (rather than prescriptive) about the utility of applying a meta-design to solve meta-requirements. Theory can also be related to the kinds of artifacts produced by DSRIS, which according to March and Smith (1995) may be constructs, models, methods and/or instantiations. For Winter (2008) theories should be considered a fifth (intermediate) type of artifact. In contrast, Gregor and Jones (2007) take a "broad view of theory" which encompasses constructs, models and methods, and where only instantiations correspond to the (material) artifact as such. Theory in this last sense is equivalent to what is termed elsewhere conjectures, models, frameworks, or bodies of knowledge, so the three outputs of design science, besides the instantiated artifact, are regarded as "components of theory" (Gregor & Jones, 2007).

constructs, methods and models.

With the options being (a) prescriptive design theory, (b) predictive utility theory, (c) an additional intermediate artifact or (d) all abstract artifacts, this research adopts the last view of theory within DSRIS (d) as composed of constructs, models and methods. This choice leads to a theoretical contribution that includes design process knowledge (methods), as well as design product knowledge (models), using a specific set of constructs that results in an instantiated artifact that coherently applies those theoretical elements. The concepts of coordination, from an information-processing view, are combined with the concepts from emergence and represented through an agent-based model developed with a specific methodology that is informed by simulation and multi-agent systems. The resulting simulation model constitutes the instantiated artifact. This choice implies an intricate relationship between the theoretical artifacts and the instantiation, which is used for operationalizing and testing them.

According to Iivari (2007), the different types of knowledge produced is what determines the epistemology underlying DSRIS. Gregor (2006), however, has strongly argued that the type of theory produced by ISR should not depend on the underlying paradigm; for her, theory is independent from specific ontological or epistemological choices. Nonetheless, both recognize the importance of making explicit choices about the philosophy underlying the research.

The research philosophy is…

The philosophical underpinning of this research follows a *Simonized* worldview in which scientific discovery is understood as problem solving and is achieved through design under the restrictions posed by bounded rationality (Simon, 1955; Simon, Langley, & Bradshaw, 1981). This philosophy is present not only in design science research but also in the theoretical background of coordination (as seen in the next chapter). In ontological terms, this research follows critical realism, which takes a realist view in the ontological domain, while at the same time avoiding the trappings of naïve realism attached to the positivist epistemological realm (Mingers, 2004). Real-world mechanisms are viewed as producing actual events that can be empirically observed, while at the same time the resulting production of knowledge is viewed as a human, socially and historically conditioned, activity. In this research, coordination issues and ICT are seen as objects of design and study that can be observed empirically, but are given meaning only through the context of the domain of application and in relation to a particular knowledge base. This fits both with the socio-technical tradition in IS, as well as with the notion of an ICT artifact in design science – which can be seen as resting in the work of Orlikowski and others, e.g. (Orlikowski, 2000). This fit has been recognized by scholars that propose critical realism as an adequate ontology for ISR (Mingers, 2004) and DSRIS in particular (Carlsson, 2006).

critical realist and

Although DSRIS is not specific in terms of an underlying epistemology, it may be seen as rooted in pragmatism in the sense that it emphasizes utility (the measure of truth in pragmatism) (Hevner *et al.*, 2004). This assumption, although widely held, does not hold for all kinds of DSRIS, making it open to alternative epistemologies, such as interpretivism (Iivari, 2007; Klabbers, 2006; Niehaves, 2007). In this research, interpretivism is the epistemological basis that aims at a contextualized understanding of coordination and ICT, connecting the critical realist ontological assumptions with the observation and validation methods. The case studies are interpretive in the sense that they approach the empirical observations through the lens provided by the conceptual framework and interpret their meaning within the context of the cases. They do not aim at generalizations or testing of hypotheses but rather at confronting the theoretical notions with situated observations and interpreting those observations both within the conceptual framework and also considering alternative views. Validation of the simulation model also uses interpretivism because it does not aim at validating the closeness between the model behavior and the real-world behavior through quantitative statistical techniques, but rather at evaluating the model as an artifact for comparing coordination mechanisms and experimenting with new ones (which have not yet been implemented and for which there is no "real" behavior to compare with). As Chapter 6 will argue, the model should not be seen as a universally valid representation of coordination in crisis response but rather a means of exploring the divergent assumptions embedded in different views of coordination for particular crisis scenarios.

interpretive.

Research outline

Chapter 1 (relevance): the problem.

This research is structured in the following way. This chapter uncovers the key issues surrounding coordination in crisis response and the role of ICT in supporting it. This belongs to the initial problem definition that starts the *Relevance Cycle*. The issues were determined by the application domain through literature study. Besides the coordination issues and a set of supporting ICTs and their limitations, this initial problem statement also offers an opportunity for making a contribution to the knowledge base by considering the role of emergence in extending the current understanding of coordination in crisis response.

Chapter 2 (rigor): the conceptual framework.

The *Rigor Cycle* then begins in Chapter 2 by providing a conceptual framework for grounding the research and the subsequent design. Based on literature, the information-processing view was determined as a dominant understanding of coordination in crisis response. This conceptual framework exhibits some limitations, especially when set against the implications of emergent coordination and of the role that ICT has in relation to information-processing.

Chapter 3 (relevance): the case studies.

With a clear theoretical framework for coordination, two case studies of crisis response exercises were done to provide empirical content and context to the meta-requirements offered in the initial coordination. Chapter 3 thus constitutes the second step in the *Relevance Cycle* through which the requirements are revised using the information-processing view as lens. The first case study identifies dependencies between activities and coordination mechanisms used to manage them, including support from ICT. The second case study focuses on the role of information management in order to further study the connection between coordination and ICT. It does so by combining coordination issues with information quality issues to show current hurdles and opportunities for improvement, extending and adding focus to the initial guidelines for crisis response information systems.

Chapter 4 (rigor): additional concepts.

The research continues in Chapter 4 with a second step in the *Rigor Cycle* in which additional foundations are presented to extend the understanding of coordination. Using literature on emergence in general and emergent coordination in particular offered the concepts that needed to be considered for extending the information-processing view of coordination. This led to the field of agents and multi-agent systems, where both the topics of coordination and emergence have been previously researched.

Chapter 5 (design): simulation.

The *Design Cycle* then begins in Chapter 5 which presents the development of a simulation model used to compare between different coordination mechanisms in a particular crisis response scenario. The chapter describes the process of developing the agent-based simulation. An Appendix is provided with the details of the technical analysis and design of the simulation model as a software product.

Chapter 6 (design): validation / experiments.

The second component of the *Design Cycle* is the evaluation of the artifact which in our case corresponds to the validation of the simulation model and the experiments to compare coordination mechanisms and develop theory. The validation, experimental design and the results are presented in Chapter 6.

Chapter 7: Epilogue.

The contributions to the knowledge base are summarized in the Epilogue which is presented in Chapter 7 providing a final answer to the initial research questions together with some directions for future research.

2 The Information-Processing View of Coordination in Crisis Response

2.1 Introduction

The previous chapter stated that in the event of a crisis it is usually required to deploy a network of response agencies, including police, fire and medical services. These need to interact with each other as well as with volunteer groups, NGOs, government agencies, and the press. The speed and accuracy with which this inter-organizational *ad hoc* response network becomes aware and takes action is critical for managing the crisis. Both speed and accuracy depend on efficient and effective coordination. During a crisis or emergency "no single organization has all the resources to alleviate the effects" (Bui *et al.*, 2000). This means that resources have to be shared between the response agencies and this requires coordination across a network that changes as the response evolves. But we have yet to clearly establish what coordination means within crisis response.

Coordination is critical for crisis response.

Several definitions of coordination have been used in crisis response literature. These definitions are usually taken from different fields, for example: (1) "the degree to which there are adequate linkages among organizational parts, i.e., among specific task performances as well as among subunits of the organization, so that organizational objectives can be accomplished" (Dynes & Aguirre, 1979); (2) "the act of working together harmoniously" (van Veelen, Storms, & van Aart, 2006), taken from (Malone & Crowston, 1990); or (3) "the process by which resources and activities involving more than one entity are managed" (Leidner *et al.*, 2009). This diversity of definitions of coordination illustrates the difficulty in defining it and the variety of starting points for studying it (Malone & Crowston, 1990).

Coordination can be defined as…

In response to this diversity, a now widely accepted definition of coordination was established by Malone and Crowston (1990, 1994). They started with a broad dictionary-based definition of coordination as "the act of working together harmoniously" and developed it into a narrow definition: "the act of managing interdependencies between activities performed to achieve a goal" or simply "managing dependencies between activities". The ensuing "coordination theory" is mainly rooted in Galbraith´s (1973, 1974) organizational information-processing (I-P) view. This view has special appeal because it offers a way to think about optimizing organizational structures to reduce coordination costs (Kling *et al.*, 2001). Accordingly, this view can be traced back to organizational design theories (March & Simon, 1958; Mintzberg, 1979; Thompson, 1967). This chapter presents the I-P view of coordination as dominant in the field of crisis response together with some of the limitations it has and what it implies for the role of ICT.

"managing dependencies between activities" (Malone & Crowston).

2.2 The View of Coordination in Crisis Response

Table 2-1 presents a list of some of the previous research related to coordination in crisis response.

Table 2-1 Studies of coordination in crisis response

Source	View of coordination	Setting
(Bui & Lee, 1999)	I-P view, based on (Malone & Crowston, 1994).	Decision-support framework for crisis action procedures.
(Smith & Dowell, 2000)	I-P view, based on (March & Simon, 1958; Mintzberg, 1979).	Case study of a railway accident focusing on distributed decision-making and coordination.
(Bigley & Roberts, 2001)	I-P view, based on (March & Simon, 1958)	Study of the use of the Incident Command System (ICS) in a fire department.
(Shen & Shaw, 2004)	I-P view, based on (Malone & Crowston, 1994).	Case study of the ICS to explore coordination and ICT.
(Comfort, Dunn, *et al.*, 2004)	I-P view, based on (Simon, 1996) and complex adaptive systems.	Coordination with decision-support for complex environments.
(Dawes *et al.*, 2004)	Indirectly the I-P view through (Argyres, 1999).	Explores the use of ICT during the 9/11 response.
(Chen *et al.*, 2005)	I-P view, based on (Malone & Crowston, 1994).	Design requirements for an emergency response system.
(Chen & Decker, 2005)	I-P view, based on (Malone & Crowston, 1994).	Experiments with coordination algorithms in an emergency medical information system.
(Comfort & Kapucu, 2006)	Framework based on complex adaptive systems.	Analysis of inter-organizational coordination in 9/11 response.
(van Veelen *et al.*, 2006)	I-P view, based on (Malone & Crowston, 1994).	Classifies coordination strategies in crisis organizations.
(Chen *et al.*, 2007)	Indirectly the I-P view through (Shen & Shaw, 2004)	Crisis management information systems design principles.
(Rietjens *et al.*, 2007)	I-P view, based on (Galbraith, 1974).	Theoretical framework for coordination to study empirical data in humanitarian operations.
(Chen *et al.*, 2008)	Indirectly the I-P view through (Raghu, Jayaraman, & Rao, 2004).	Coordination framework applied in the analysis of a train derailment incident.
(Leidner *et al.*, 2009)	I-P View based on (Malone & Crowston, 1990)	Case study of the SARS and Asian Tsunami disasters focusing on ICT.

Although Table 2-1 is not exhaustive, it does illustrate a preference in crisis response literature to treat coordination explicitly or implicitly through the I-P view. Six papers in the table cite Malone and Crowston directly as the source for their understanding of coordination, although in one case the authors claim that this choice is based on familiarity, rather than endorsement (Bui & Lee, 1999). Indeed, it is hard to say whether citing Malone and Crowston is a result of strictly endorsing the information-processing view or motivated by the fact that it is widely accepted as an appropriate and straightforward definition. This is partly a consequence of Malone and Crowston's initial intention of creating a generic theory of coordination which would be interdisciplinary, seeking the common thread in previous and diverse studies related to coordination. Although Malone and Crowston cite many disciplines as informing their theory of coordination (including computer science, organization theory, management science, economics, linguistics, and psychology), they were also aiming at an emergent theory of coordination, which could be general in the same sense that systems theory and cybernetics intended for their own set of concepts (Malone & Crowston, 1990, 1994). In any case, it remains as a clear, popular and influential understanding of coordination – Google Scholar reports 1721 cites to the 1994 paper on October 6, 2009 – with a dominant place in the crisis response literature.

Many refer to coordination in terms of Malone and Crowston (1994);

Other papers in the table go more directly into the I-P view by citing the earlier work of Galbraith, Mintzberg or March and Simon, or indirectly (tacitly) by citing other works that are based on the I-P view. Those that refer to March and Simon (Bigley & Roberts, 2001; Smith & Dowell, 2000) emphasize the issues surrounding the conflict between centralized and distributed decision making and the impact that hierarchy has on such conflict and on the possible re-designs that the organization might be subject to. Rietjens *et al.* (2007) are the only ones in the table to use the original Galbraith I-P view explicitly as an analytical typology. The table shows that the papers span a decade with the same trend, although it is possible to look further back at the work of Dynes and Quarantelli – e.g. (Dynes & Aguirre, 1979) – which address coordination in a pre-Malone and Crowston context by referring to March and Simon (1958) as well as Thompson (1967), while still making it clear that feedback and emergence are critical during disaster response.

others use the I-P view directly…

Dawes *et al.* (2004) indirectly refer to Malone through Argyres (1999), although they question whether the bounded rationality understanding of users on which the I-P view is based is adequate for crisis response (as discussed n section 2.5). The papers by Comfort (Comfort, Dunn, *et al.* 2004; Comfort & Kapucu, 2006) cite the I-P view, but are also rooted in complex adaptive systems, which already hints at the possibility that when emphasis is placed on complexity and emergence, the I-P view might need to be nuanced, extended or used critically.

or indirectly,

The examples on the table exhibit a variety of settings, showing that the I-P view is not limited by any particular organizational context or type of crisis. This means that the I-P view of coordination forms the basis for an interdisciplinary understanding of coordination, as Malone and Crowston intended. This prompts a closer look into the I-P view of coordination and a critique regarding its relevance for crisis response in particular.

in a variety of settings.

2.3 Background: The Information-Processing View of Organizations

The information processing (I-P) view...

The information-processing view of organizations is based on the proposition that "the greater the uncertainty of the task, the greater the amount of information that has to be processed between decision makers during its execution" (Galbraith, 1973, p. 4). Uncertainty in turn is defined as "the difference between the amount of information required to perform a task and the amount of information already possessed by the organization" (*ibid.*, p. 5). And the amount of information needed to perform a task depends on the diversity of its outputs, the number of inputs and the level of difficulty (*ibid.*, p. 5). The task or challenge for organizational design is to devise the fit between the information processing needs and capabilities in order to obtain optimal performance. This follows the premise that organizations need quality information to cope with environmental uncertainty and to improve their decision making (Premkumar, Ramamurthy, & Saunders, 2005).

is related to coordination and based on...

In coordination terms, uncertainty, along with complexity and inter-dependencies, creates information processing needs, which are dealt with by organizing elements that facilitate coordination (Gosain, Lee, & Kim, 2005). The connection between information-processing and coordination is based on the understanding that as the amount of uncertainty increases, organizations adopt coordination mechanisms which allow them to handle more information effectively (Galbraith, 1974). The organization can thus either reduce the amount of information that is processed or increase its capacity to handle more information (Galbraith, 1973, pp. 14-15). To do so, the key is to identify the dependencies and coordination mechanisms that can unlock such redesign (Malone & Crowston, 1994; Malone *et al.*, 1999).

This understanding has underpinnings in Herbert Simon's bounded rationality model, according to which a "veridical picture of economic actors and institutions must incorporate the information processing limits set by their inner environments" (Simon, 1996, p. 49). In this view, firms shift the focus from substantive rationality (which is based on prediction and profit-maximizing) to bounded rationality (which is based on estimation and computation under uncertainty) to reach *satisficing* (rather than optimal) solutions (*ibid.*, pp. 25-27). Bounded rationality thus refers to

bounded rationality.

> *"information-processing limitations in computing optima from known preference or utility information, unreliable probability information about complex environmental contingencies and the absence of a well-defined set of alternatives, especially in a turbulent world that may produce situations that never existed before" (Ciborra, 1993, p. 23).*

At the individual level, bounded or limited rationality follows the replacement of the notion of *homo economicus* – in which humans are perfectly rational and knowledge is fully accessible – with the notion that rationality depends on the (limited) access to information and the (limited) computational capacities of man (Simon, 1955). As an organism of bounded knowledge and ability, the human individual is limited in computing optima (finding solutions) and faced with the absence of a well-defined and complete set of alternatives.

Extending the notion of bounded rationality from individuals to groups, limited rationality sees an organization as "a problem-facing and problem-solving device operating in an uncertain environment, where information and knowledge are not fully accessible" (Ciborra, 1993, p. 24). In order to cope with this, organizations become coordination and control mechanisms (*ibid.*, p. 24). Accordingly, there are a number of non-mutually exclusive organizational design strategies that can be adopted. Galbraith (1973, 1974) generalized them into a design framework, composed of seven strategies: 1) rules and programs, 2) hierarchical referral, 3) goal setting, 4) creation of slack resources, 5) creation of self-contained tasks, 6) investment in vertical information systems, and 7) creation of lateral relations.

Following March and Simon, Galbraith (1973, p. 10) established *rules and programs* as the simplest method of coordination by specifying the necessary behaviors in advance of their execution; this reduces the amount of communication needed, eliminating the need for treating each situation as new and providing stability. However, new situations will still arrive, so new information needs to be collected and new problem solving activities need to be used. *Hierarchical referral* enters the picture when these new problems are referred up the hierarchy to managerial roles that have the information to make the new decision (*ibid.*, p. 11). But this hierarchy can become overloaded as exceptions increase. Thus, the decision needs to be pushed back down the hierarchy, close to the points of action, introducing a shift from supervision to selection of skilled workers. In order to prevent conflicting preferences between the local and global levels, *goal setting* now needs to be employed to maintain targets for the primary dependencies (*ibid.*, pp. 12-13).

Organizational design strategies include…

The ability of an organization to coordinate through rules, hierarchy and goal setting depends on how frequently exceptions occur and on the capacity of the hierarchy to handle them (*ibid.*, p. 14). With more uncertainty and more exceptions the hierarchy becomes overloaded and the organization needs to reduce the amount of information-processing required either through slack resources or self-contained tasks. *Creation of slack resources*, which again follow Simon's cognitive limits theory of organizations, reduce the need for information-processing by absorbing increased uncertainty (*ibid.*, p. 24). The trade-off is that by using additional resources, organizations also reduce performance standards. In crisis response, slack resources are for the most part not viable or desirable, due to the already limited amount of available resources, but sometimes slack resources are "accidental" when for example NGOs and military organizations compete for assistance projects and end up duplicating relief efforts (Rietjens *et al.*, 2007). *Creation of self-contained tasks* also reduces information-processing needs by reducing output diversity and division of labor while moving the decision points closer to the source of information. However, there is a loss of economies of scale and an increase in redundancy (Galbraith, 1973, pp. 26-29). During crisis response, self-contained tasks are heavily used (given the specialized nature of professional responders) but when they are not centrally coordinated they also end up in duplication (Rietjens *et al.*, 2007).

reducing I-P needs or...

Rather than reducing the need for information processing, the organization can opt for increasing its information processing capacity either through vertical information systems or through creation of lateral relationships. An *investment in a vertical information system* should increase the capacity of communication channels and introduce new decision mechanisms (Galbraith, 1973, p. 30). There is, however, a cost and a risk attached to this investment (not to mention the additional difficulty when coordination needs are of an inter-organizational nature). During a crisis, information systems can contribute to coordination (as shown in Chapter 1), but some organizations are independent of each other and this lack of subordination makes (vertical) information systems difficult to realize and sustain (Rietjens *et al.*, 2007). *Creation of lateral relationships* is the final design alternative which replaces hierarchy with cooperation among peers; it reduces the number of decisions being referred upward and increases the I-P capacity of the organization (Galbraith, 1973, p. 46). This cooperation can be implemented through: 1) direct contact between managers, 2) liaison roles, 3) task forces, 4) teams, 5) integrating roles, 6) linking-managerial roles, or 7) matrix designs of dual authority (*ibid.*, p. 48). Lateral relations are frequently seen in emergency operations where several roles are dedicated to liaison tasks; however, this coordination mechanism is challenged by the (lack of) reliability of the information received by liaison personnel (Rietjens *et al.*, 2007).

increasing I-P capabilities.

2.4 The Information-Processing View of Coordination

Although Malone and Crowston's theory of coordination is interdisciplinary and generic, it draws heavily upon the information-processing view of organizations. For them coordination implies a relationship between dependencies and processes or mechanisms used to manage them. The basic organizational coordination mechanisms are the first three organizational design strategies described above: rules or programs, hierarchical referral and goal setting. These can be traced back to March and Simon (1958) and to Mintzberg (1979) and can also be labeled as: standardization, mediation and mutual adjustment, respectively. For their part, dependencies can be classified into: resource flow, resource fit and resource sharing (Malone & Crowston, 1994). This section presents a conceptual framework that illustrates this relationship between dependencies and coordination mechanisms.

Coordination mechanisms manage dependencies.

Figure 2-1 offers a visual interpretation of the conceptual framework that constitutes the information-processing view of coordination. On the top of the figure there are three kinds of dependencies between activities, which are the source of information-processing/coordination needs. On the bottom of the figure are three kinds of coordination mechanisms that handle those needs by providing an increase in information processing capabilities. The following subsections describe each component in more detail.

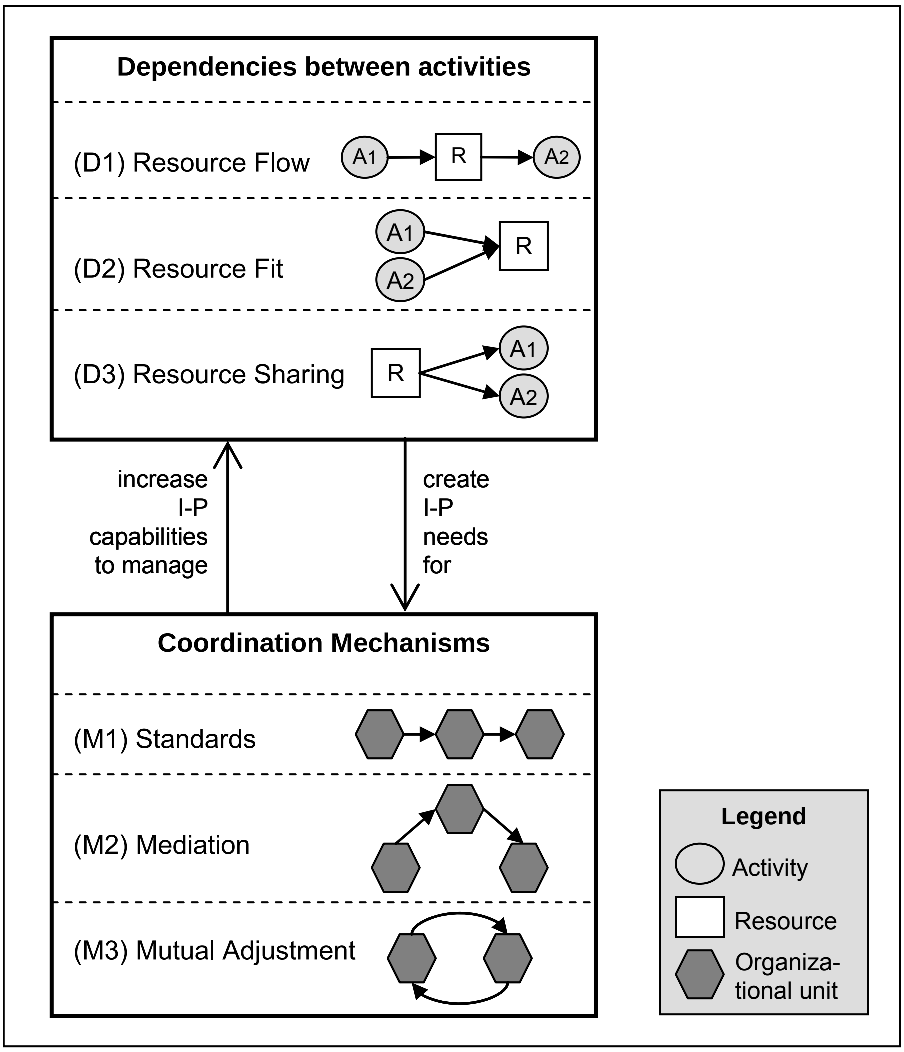

Figure 2-1 Framework for the information-processing view of coordination

Coordination dependencies between activities

The first question that the framework in Figure 2-1 helps us address is: what is it that needs to be coordinated? To answers this we go back to the definition of coordination: managing dependencies between activities. "From the perspective of coordination theory, whenever there is a dependency between two activities, there is an opportunity (often a need) to manage it" (Herman & Malone, 2003). Moreover, identifying dependencies and coordination mechanisms offers special leverage for redesigning processes (Malone *et al.*, 1999). Interdependencies refer to goal-relevant relationships between activities; if there is no interdependence, there is nothing to coordinate (Malone & Crowston, 1990). Those dependencies were initially classified into: prerequisite (producer/consumer), shared resources, simultaneity and task/subtask (Malone & Crowston, 1990, 1994). More generically, they were later referred to as: flow, fit or sharing (Malone *et al.*, 1999).

Coordination dependencies are classified into:

Flow (D1),

A flow dependency occurs when a resource flows from one activity into another (Herman & Malone, 2003; Malone *et al.*, 1999). This dependency occurs on most processes and is the focus of many process mapping techniques (i.e. flowcharting). It can be seen as composed of three more specific kinds of dependencies: prerequisite constraints (production before use), accessibility constraints (produced resource must be made available for use) and usability constraints (resource produced should be usable by consuming activity). In other words, managing a flow dependency means having the right thing in the right place at the right time. For example, during emergency response there are flow dependencies between tasks in the pre-incident, during incident and recovery phases. This interleaving of response processes, requires the establishment of coordination goals to avoid conflicts, overlapping and duplication, among others (R. Chen *et al.*, 2008).

Fit (D2),

A fit dependency occurs when multiple activities produce a single resource (Herman & Malone, 2003; Malone *et al.*, 1999). The unique aspect of a fit dependency is that each producer could independently produce what appears to be a usable component of the resource, but the fit among the producers must also be managed. During an emergency, fit dependencies imply interaction among activities or trade off effects between them (Shen & Shaw, 2004).

and Sharing (D3).

A sharing dependency occurs when two or more activities use the same resource (Herman & Malone, 2003; Malone *et al.*, 1999). This occurs when a reusable resource is used by multiple activities or when a divisible resource must be divided among competing processes. In the response to an extreme event, various organizations must share information and resources under the principle that risk and goals are also shared between them (Comfort & Kapucu, 2006).

Coordination mechanisms

Coordination mechanisms …

Once the dependencies that create information processing needs are established, the next question is how to increase the information processing capabilities to handle them. The answer lies in coordination mechanisms, which are the methods or tools to manage dependencies (Malone *et al.*, 1999; Simatupang, Sandroto, & Lubis, 2004; Xu & Beamon, 2006). When the number of dependencies is high, organizations need to apply more coordination mechanisms to control information and resource flows (Song, Woo, & Rao, 2007). Coordination mechanisms are first enacted through routines that tend to be arranged hierarchically, according to specialization and functional decomposition of complex tasks, resulting in lower capacity for flexible adaptation (Ciborra, 1993). As a result, the organization is "forced" to shift from standards or plans to hierarchy. When the hierarchy becomes overloaded, it must rely on mutual adjustment and goal setting to make up for the lack of flexibility. The key is to consider the alternative coordination mechanisms available for the same dependency (Crowston, 2003); and the challenge is to select the appropriate coordination mechanism based on their relative costs (Xu & Beamon, 2006).

are classified into:

In crisis response, existing, well-understood, coordination mechanisms provide an organization the ability to quickly pull existing (and sometimes dormant) resources and capabilities into action (Leidner *et al.*, 2009). Coordination mechanisms may be specific (e.g. code management systems to control software changes) or general (e.g. hierarchies or markets to manage assignment of activities to actors) (Crowston, 2003). In the I-P view, coordination mechanisms can be classified (after Thompson, March and Simon, Galbraith *et al.*) as: standards, mediation and mutual adjustment.

Coordination mechanisms that fall into the standards approach can also be found in literature as coordination *by rules*, *by programs*, or *by plans* (Dynes & Aguirre, 1979; March & Simon, 1958). For Simon (1996, p. 42), standardization (achieved through agreed-upon assumptions and specifications) is an effective way to deal with uncertainty. In this case, coordination is achieved by following a predefined plan or standard (e.g. a workflow). Regulation is thus external, and based on some control system (i.e. rewards or sanctions). In crisis response, task flow dependencies can be managed through standards or plans, implemented in the pre-incident phase through training and exercising; during the indent, they can be implemented through routines, notifications or tracking; in the recovery phase they can be implemented through task sequencing (Chen *et al.*, 2008). Planning can thus be seen as the number one coordination mechanism for flow dependencies in crisis response (Shen & Shaw, 2004).

Standards (M1),

Coordination by mediation is another kind of mechanism, also known as coordination *by hierarchy* (Galbraith, 1974) or *by direct supervision* (Mintzberg, 1979), although the latter two might imply pre-existing lines of authority, whereas mediation alone might be contingent or aimed at conflict resolution. In this case, coordination between two activities or actors is achieved through the mediation of a third actor or organizational unit, typically one level up in the hierarchy. Mediation through hierarchical control is an integral part of crisis response, embedded into the organizational structures of response agencies, especially when they have a military command-and-control tradition. Hierarchies can contribute to mediating decision-making and resource distribution during a crisis. However, the ensuing order must be balanced with the equally important need to be flexible, open, agile and adaptive (Comfort, Dunn, *et al.* 2004; Harrald, 2006).

Mediation (M2),

Coordination by mutual adjustment (Mintzberg, 1979; Thompson, 1967) is the third type of coordination mechanism. In this approach, also denominated coordination *by feedback* (Dynes & Aguirre, 1979; March & Simon, 1958), individual responses are negotiated and adapted according to the responses of others. This approach relies on internal control based on new information that leads to adjustment or correction. In crisis response, mutual adjustment is a typical mechanism for avoiding conflicts and negotiating goals (Shen & Shaw, 2004). Moreover, as we mentioned before, crises create extreme uncertainty, thus causing the organizational structure to move in the direction of mutual adjustment and away from plans and standards (Dynes & Aguirre, 1979).

and Mutual adjustment (M3).

Above, it has been argued that the I-P view of coordination, embodied in Malone and Crowston's influential work, is based on organizational design and bounded rationality. It has also been claimed that this view is favored by most studies of coordination in crisis response. But is this understanding of coordination sufficient and/or adequate given the complexity and uncertainty of a crisis environment and the nature of an *ad hoc* response network? Furthermore, what does the I-P view imply in terms of the role of ICT in supporting coordination?

2.5 Limitations of the I-P View of Coordination

The information processing view of coordination relates information processing needs to the uncertainty and difficulty of tasks. In Chapter 1 it is argued that crisis response is challenged precisely by uncertainty, heterogeneity and information problems, among other difficulties. Thus, crisis or emergency response poses a unique and in some cases disastrous complexity, often linked to lack of effective or efficient coordination. Despite the unique challenges, crisis response is still often structured following I-P organizational designs, including standard operating procedures and hierarchical command and control. It is also apparent from the literature that the I-P view still guides much of the discussion on crisis response coordination. This section discusses the main limitations of the I-P view of coordination which are especially relevant for the domain of crisis response and which have opened up the space for extensions or alternative views. It also re-examines the role of ICT in supporting coordination, taking into account the I-P view and its limitations.

The I-P view emphasizes standards and hierarchy,

The information-processing view of coordination can be seen to assume that coordination is first tackled by designing formal structures then, as task or environmental uncertainty increase, coordination moves towards less formal interpersonal liaisons (Bechky, 2006). In other words, it places standardization before hierarchy and hierarchy before mutual adjustment (the last resort). But as others have pointed out (Dynes & Aguirre, 1979; Faraj & Xiao, 2006) this emphasis may result in neglecting or not adequately or explicitly supporting other forms of coordination. Indeed, this potential drawback was recognized a long time ago, e.g. Mintzberg and McHugh (1985) state that in adhocracies "[c]oordination by direct supervision [mediation] and standardization are discouraged, as are the more formalized aspects of structure that support them, such as hierarchy, performance controls, and rules."

in part due to "near-decomposability".

The emphasis on hierarchy is partly embedded in the information-processing view due to a simplistic adoption of Herbert Simon's ideas on hierarchy. For Simon (2001), coordination creates costs, for example in the form of communication costs or the cost of motivating members to work toward a common goal. To reduce this cost, organizations divide their activities to create as much independence as possible between divisions and departments. This results in a principle of organizational design according to which organizations should "divide up the work among components in such a way as to minimize the needs for coordination". To support his argument, Simon brings to mind examples from natural and artificial complex systems which, according to him, are hierarchical in structure. He then goes on to argue that components at each level of the hierarchy are not independent but rather more densely connected, giving way to his notion of "near-decomposability". A near decomposable complex system is arranged as a boxes-within-boxes hierarchy where interactions *within* boxes take place much more densely and rapidly than *between* boxes. The main point to be drawn from this notion is that complex systems must "somehow be created to meet the needs of coordination, and the prospects for the emergence of an effective complex system are much greater if it has a nearly-decomposable architecture, than if the interconnections are less departmentalized".

In a multi-disciplinary crisis response network, near-decomposability cannot be achieved in the same straightforward manner as in more closed and stable organizations by simply departmentalizing activities and responsibilities. A public *ad hoc* network such as that formed for crisis response is different from a traditional organizational hierarchy because it requires autonomous organizations to work together in a collaborative, non-bureaucratic structure with very different coordination challenges (Janssen & Kuk, 2007). During a crisis, when there is a need for inter-agency response, the organization can be better characterized as a temporary (Bechky, 2006), fast-response (Faraj & Xiao, 2006) adhocracy (Mintzberg & McHugh, 1985).

But this is limited for crisis response.

Assuming that coordination of a crisis response network can be managed by applying information-processing based coordination theory uncritically can lead to misguided organizational designs or ineffective uses of technology for supporting coordination. This leads to an exploration of alternative views or extensions to the I-P view of coordination that do not place the emphasis on standards and hierarchical structures, or that do not assume that mutual adjustment is the last resort, but rather an integral part of coordination in certain types of organizations.

Alternatives and extensions include:

Alternatives and extensions to the I-P view

Lewis *et al.* (2001) consider Malone and Crowston's view of coordination as mainly collaborative (i.e. where participants have shared goals). This assumption creates the risk that inaccurate assessments of the value of choices taken by different participants can lead to apparently harmonious but actually unstable situations. As a result, they claim that (collaborative) coordination theory places too much emphasis on efficiency and too little on the quality of the outcomes. In order to avoid the risk of neglecting goal divergence in favor of smooth working, they suggest an extension of Malone and Crowston's theory of coordination, which includes dispute moderation or elimination to deal with potential conflicts before any (collaborative) coordination mechanism is put in place.

Similarly, Klein (1998) established three layers for coordination support, where the first is aimed at supporting communication, the second collaboration and the third (after the previous two are in place) coordination. Klein's account of "coordination science" differs from Malone and Crowston in aiming explicitly for collaboration (rather than assuming it). Communication support should allow participants in the decision process to share information. Collaboration support should allow participants to collaboratively update a shared set of decisions. The top-level coordination support amounts to "ensuring the collaborative actions of the individuals working on a shared set of decisions are coordinated to achieve the desired result efficiently". As with Lewis *et al.*, this approach considers conflict management as a key technology for supporting coordination. During a crisis, the assumption that response organizations have shared goals and collaborate towards a common goal (e.g. containing the crisis or saving lives) is a simplistic assumption which neglects that different agencies will have different priorities at different times, will compete for resources, and will have to answer to different people. This makes the previous two approaches to coordination relevant for crisis response, in order to explicitly deal with collaboration.

collaborative coordination,

According to Kling *et al.* (2001), the I-P formulations embedded in Malone and Crowston's theory of coordination emphasize static and relatively optimal solutions to organizational problems – where optimality consists in minimizing the cost of coordination. For them, this results in an incomplete understanding of how to cope with dynamic organizational problems that arise from changing coordination practices. The emphasis on information-processing can lead to an overemphasis on coordination as formal information exchange, instead of interconnection of distinct groups. For Kling *et al.*, the shift in emphasis from the information to the groups that exchange it requires using other theoretical perspectives in addition to the I-P view. They suggest including behavioral theories from organizational sociology and institutional economics. These theories help uncover the institutional arrangements that permeate the organization with external coordination issues, including divergence in the logic of coordination that each organization uses. This suggestion is relevant for multi-disciplinary crisis response in which heterogeneous organizations form a dynamic response network. Under these circumstances, it is no longer possible to expect that a single overarching approach, through plans or standards for information exchange alone, will result in coordinated action between all involved agencies.

behavioral theories,

Typically, the I-P view is seen as a way to match dependencies to coordination mechanisms beforehand (in planning mode); hence the emphasis on organizational design. The resulting selection of mechanisms is often supported by technologies that are expected to manage the dependencies in a prescribed manner. Orlikowski, along with other scholars of the socio-technical school, has developed a critique of this kind of view in which technology is rather static and almost independent from the context of application. Her notion of "technology-in-practice" revises this simplistic assumption by drawing attention to the fact that technology changes in the same way as all social structures: through human action. Knowledgeable human action continually engages with the technology constituting and reconstituting structures of using the technology, particularly through emergence and improvisation (Orlikowski, 2000). This is equally true of coordination, where she advocates for "situated coordination", which explicitly examines how organization emerges out of ongoing and mundane interactions between individuals and technology (Orlikowski & Barley, 2001). Typical studies of situated coordination thus study "how workers orient to each other and to their tasks using emerging information and technologies at hand", or in other words "co-oriented individuals who jointly use tools and artifacts to solve problems in the here-and-now". In a way, this suggests that even in the case where standardized or hierarchical coordination mechanisms are designed, they are constantly subjected to the mutual adjustment between individuals and also between individuals and the technology that is expected to embody those coordination mechanisms. This shifts the emphasis from organizing as design to organizing as an "activity that simultaneously shapes and is shaped by the properties of the technologies that people use" (Orlikowski & Barley, 2001). Chapter 1 already discussed the importance of improvisation during crisis response, which includes using technology in novel ways and restructuring it in "real-time". In addition, it mentioned how sophisticated and official technological support was sometimes replaced by emergent, civilian-based social software created as the crisis is still ongoing. This is amenable of being studied and interpreted from a "situated" perspective.

situated coordination,

The I-P view of coordination provides a conceptual link between the use of information systems and organizational form by assessing dependencies and coordination mechanisms mainly as information processing activities. Not far from the situated perspective, but closer to an extension of the I-P view than an alternative, Leidner *et al.* (2009) suggest that by looking at coordination through the perspective of governance is more adequate to uncover the role of governance mechanisms in forming the backbone of the *ad hoc* coordination required in crisis response. Instead of focusing on dependencies and coordination mechanism as information processing activities, they identified the crisis, information and ICT structures that must be put in place during crises. Such structures then become the actual coordination mechanisms through which ICT governance is achieved. A difference with other governance studies is that rather than exhibiting stable governance constructs, crisis organizations use different governance mechanisms for different types of decisions concerning ICT. The coordination mechanisms are then reinterpreted not as ways to reduce information processing needs or increasing information processing capabilities, but rather as a way in which resources are converted into actions. For example, the informational structure embedded in Singaporean information transparency policy acted as a coordination mechanism during the response to the SARS outbreak in 2003. It contributed to converting leadership (a resource) into stakeholder commitment (an action) by increasing awareness and building trust in the government's response plan.

governance,

Role-based coordination, as discussed by Bechky (2006), challenges the information-processing view of coordination by suggesting that roles are fundamental for coordination, especially in temporary organizations, such as those that come together in the event of a crisis and then disband when the crisis is resolved. For example, by thanking each other, admonishing (assertively pointing out mistakes or asking for help) and using humor, participants quickly learn and negotiate the role structures which are only partially known prior to the group interaction. This role-based coordination is important when there are no previous standards or clearly established hierarchy that participants can use to carry out their activities in collaboration with other participants that they have often never worked with before. During a crisis, the use of uniforms, badges, tacit codes of behavior and body language can be added as additional ways in which participants make sense of their role and that of other participants contributing to a coordinated response.

role-based coordination,

Practice-based coordination (Faraj & Xiao, 2006) also challenges the information-processing view of coordination by stressing that coordination is emergent as well as structured and that sometimes (e.g. in fast-response organizations) it is desirable that emergent coordination occurs to deal with an abnormal trajectory. This suggests a need for subverting the standard or hierarchical mechanisms of coordination when an abnormal trajectory so requires it. Two kinds of practice-based coordination are expertise and dialogic coordination. Expertise coordination is based on knowledge, rather than standards or authority, prompting the emergence of new coordination structures as a response to the knowledge-based requirements of the situation. A typical example of this in crisis response is the shift in command or leadership when the nature of the emergency requires it. For instance, when a "normal" fire situation becomes a toxic gas cloud as in the example inside the Vignette in Chapter 1, this

and practice-based coordination.

might require a different kind of expert to lead the response efforts. For its part, dialogic coordination may challenge the structure (hierarchy) when someone detects a potentially wrong decision from an upper echelon. This dialogic coordination is an example of mutual adjustment taking place within (or rather as a complement of) a hierarchical mechanism, not replacing it, but challenging it for a specific situation and then reverting back to it without a conscious and previous design process as the simplified I-P view would assume.

Revising the role of ICT for crisis response coordination

Integrating different processes and levels of ICT sophistication across organizations requires an examination of the role of ICT and how it can provide the needed coordination mechanism to share resources and capabilities (Janssen & Kuk, 2007). Coordination can occur with or without ICT support; in the first case it can be referred to as media or computer supported coordination (van Laere, 2003, p. 7), which is addressed in this section from the point of view of the I-P view and its limitations. In the information-processing view, ICT is seen as a way to enable, support or reduce the cost of coordination (Crowston, 1997; Malone & Crowston, 1994; Marjanovic, 2005). This understanding is underpinned by the assumption that ICT can increase the quantity of information transmitted and received per unit of time (Argyres, 1999). Such increase in information processing capacity can reduce uncertainty in complex situations, making ICT one of the basic coordination mechanisms (Rietjens *et al.*, 2007). As a result, information processing capabilities can be linked to the level of ICT support (Premkumar *et al.*, 2005). The specific ways in which ICT can support information-processing capabilities can be seen in Chapter 1, which lists several of the available technologies that enable better information exchange, decision-making and knowledge management, among others.

ICT can increase I-P capabilities …

However, there is a major issue which is seldom addressed properly: even though the coordination of interconnected units allows for innovation and knowledge creation, it also imposes coordination costs (Cuel & Cristiani, 2005). This is equally true for computer supported coordination: while ICT enables people to shape coordination by lowering coordination costs, it also increases the complexity of coordination and in practice implies large technological and organizational investments (den Hengst & Sol, 2001). Although existing information systems increase the capability of each unit to manage local knowledge, they increase their coordination difficulties (Cuel & Cristiani, 2005). ICT can be used to solve coordination problems without substantial side effects, especially when the problems and technologies are simple and straightforward. But as coordination problems become more complex and interdependent, so do the ICTs intended to solve them (Kling *et al.*, 2001). In crisis response, an example is information retrieval support, which may aid in gathering previously unavailable or difficult to find information, but may also result in a large amount of information to be processed. Another example is that ICT may bring people together, potentially generating new dependencies that would not have been present without ICT mediation. The key is to find an adequate design and use of ICT which, despite the costs that it creates, still reduces the overall cost of coordination and, more importantly, improves response effectiveness.

but can also increase coordination costs.

Accordingly, any analysis of the role of ICT for coordination or any design of ICT to support coordination should see ICT as an information processing capability, but also consider any potential effect on information processing needs that could counteract the cost of coordination. Any new technology might result in a new form of coordination that creates new coordination challenges (Janssen & Kuk, 2007). During crisis response, ICT use might actually exacerbate the severity when the communications and computing infrastructure become damaged or due to the absence, loss, outdated nature, or inaccessibility of needed information resources (Dawes *et al.*, 2004). Moreover, there is a risk involved in assuming naively that ICT will overcome organizational and data quality problems, which are not technological in nature but rather related to lack of coordination, standardization, trust and preparedness (*ibid.*)

ICT may increase the severity of a crisis…

Since ICT does not "solve" coordination problems, but rather substitutes one set of dependencies (and their associated costs) with another, Kling *et al.* (2001) speak of the role of ICT as transforming one set of coordination problems into another which may be more or less tractable. For example, some coordination problems associated to ICT are related to the infrastructure and skills required to make technology-centered coordination work. Another perhaps more challenging one is that of coordinating worldviews (different assumptions and different purposes) that may generate conflicting requirements, design principles and contextualized uses of the technology. Thus, for Kling *et al.*, the "irony" of ICT and coordination is that the new kinds of interdependencies created by ICT may be more difficult to coordinate than the original problems.

or transform coordination problems into worse ones.

As a consequence, Kling *et al.* argue that new design techniques and institutional arrangements have the potential to make these coordination problems less severe. Fussel *et al.* (1998) also argue that it may be possible to balance the tension between the need for more information to improve coordination and the need for reduced information to conserve attention and resources. For example, ICT can help in providing information asynchronously and in aggregating it rather than providing it incrementally. As a result, ICT can reduce attention demands (information-processing needs) without reducing the usefulness of the information or generating additional information overload. This means that ICT use will only be effective when it can be easily restructured, when it can relay distribution and organizing information, and when it enables social networking (Forsman, 2007).

Through new designs and institutional support…

Efforts to implement ICT for coordination are more likely to succeed if they consider the institutional environment and the contextualized use of the technology: the key to success is thus to plan for greater complexity brought on by ICT and provide institutional and social support to facilitate the adaptation to new ICT. In crisis response, ICT assets and capabilities have already shown to be inextricably linked to non-ICT related assets and capabilities, such as skills of the information systems professionals participating in the response (Leidner *et al.*, 2009). For example, ICT for coordination support can contribute to dealing with the possibility of conflicting goals by exposing the value that different participants attach to different choices or by improving the participant's knowledge of the true effects of actions and the true value of certain states, e.g. showing them the effects of tying up scarce resources or the urgency of supplying pre-requisites for other processes (Lewis *et al.*, 2001).

the likelihood of ICT success can be increased.

Simulation enables developing insight…

In sum, ICT can reduce or increase information-processing and it can transform a set of coordination problems into another which may be more or less tractable[1]. This can be dealt with through the development of new design techniques and institutional arrangements. Simulation is one way in which this can be achieved. By providing an artificial and controlled environment, simulations permit an evaluation of different coordination strategies and supporting ICT tools prior to their implementation or deployment for real crisis situations. Simulation enables exploring different configurations related to the infrastructure and the skills that are related to ICT. Through abstraction, visualization and experiments, simulation also makes it possible for stakeholders to coordinate their potentially conflicting goals and assumptions. A simulation that integrates different crisis response disciplines and organizational levels also contributes to exposing the effects of individual actions on dependent tasks and resources.

about such design and institutional support,

A simulation model that represents specific crisis conditions and objects can be used as a testbed for assessment of ICT support for coordination, providing the necessary context for analyzing the potential utility of the ICT in a specific environment. The understanding of the potential users can also be improved by including the surrounding space and the interaction with objects which are especially relevant in crisis environments subject to a chaotic constantly changing context (Forsman, 2007). This results in the possibility of evaluating different institutional arrangements before including them in existing planning and training efforts. Moreover, such arrangements can be established in relation to specific crisis conditions, resulting in a catalogue of coordination mechanisms (whether supported with ICT or not) specifically tailored for crisis response.

as this research will show.

One instance of this type of simulation model is the main design artifact resulting from this research. Such a simulation should be built using the constructs from the I-P view contained in this chapter (dependencies, mechanisms, coordination cost). It will specifically be used to compare bottom-up mutually adjusted coordination with top-down mediated coordination. It will also illustrate the ability to simulate one such mediated coordination mechanism as an ICT supported one. This will contribute not only to extending and contextualizing the I-P view of coordination for crisis response, but also to get insight into the relative coordination costs incurred in relation to the increase (or decrease) in response efficiency and effectiveness (response time and victims).

But before presenting the development of the model, we will enter the *Relevance Cycle* to get some empirical context that can help establish the I-P view as a useful analytical framework for coordination in crisis response. Through two different case studies, the I-P constructs will be used to classify findings from crisis response exercises. Additionally, the role of ICT will be further explored in this context by looking at some of the tools that are currently being used and the benefit that they can have in terms of information quality and coordination.

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[1] This section is related to a structural problem for ICT which has been recognized for a long time under the label of "the IT productivity paradox". Much research and discussion has taken place regarding the risk that ICT investment poses when considering the uncertainty regarding productivity gains. This suggests that the value of ICT is far from guaranteed and its success has been linked to a proper recognition of contextual factors and user participation, among others.

3 Crisis Response Coordination in Practice

3.1 Crisis Response in the Port of Rotterdam

The domain of crisis response is not only of crucial interest for society in general, but also offers a rich setting for the study of coordination that can be applicable in other domains as well. If there are open inter-organizational coordination issues, they will probably surface during a crisis or emergency. Since planned observation of real crisis response is uncertain, limited and risky, using exercises, records of past responses, or computer-based simulations are common ways of dealing with this limitation in crisis response research.

In Chapter 1, some of the pressing issues related to coordination in crisis response were discussed, together with the ICTs that can be used to deal with them. Chapter 2 went on to describe the information-processing view of coordination as the dominant understanding of coordination. This background provided not only the conceptual framework of this research, but also some of the main limitations and requirements that should be addressed in order to improve coordination efficiency and effectiveness during a crisis. In terms of design science research, the I-P view of coordination constitutes the kernel theory that provides the initial knowledge base of the research.

In this chapter, the concepts are applied in practice through two case studies that are the source for adding empirical and relevant content to the initial coordination issues from Chapter 1. The first case study identifies dependencies and mechanisms for coordinating them (including ICT support) using crisis response exercises in the Port of Rotterdam (PoR) as the source of empirical observations. The second case study focuses on the role of information management to support coordination in order to identify requirements for ICT support in the same PoR setting. The context of crisis response in the PoR offers a complex and (relatively) technologically advanced environment in which to study coordination and ICT use in practice.

Crisis management is critical for large ports...

Ports, and especially mainports such as Rotterdam, have a considerable impact on the economies of regions. They are a strategic piece in global supply chains and can fuel the economy of countries like The Netherlands, whose Port of Rotterdam is the largest in Europe – third in the world after Shanghai and Singapore, or fourth when counting the recently combined port of Zhoushan/Ningbo (Port of Rotterdam Authority, 2009). However, some have doubts as to whether ports will be equally competitive in the current global conditions. The PoR contribution to Dutch GDP, for instance, although still high, has decreased from 8.3% in 1987 to 7.9% in 2002 (Statistics Netherlands, 2005). And the future looks even more challenging. After the terrorist attacks of September 11, 2001, the whole global supply chains have had an increase in their operation costs (Barnes & Oloruntoba, 2005). This means that competitiveness is now more than ever a critical issue for ports all over the world and new practices need to be implemented to deal with security and crisis management.

constantly exposed to threats.

In 2008, 421 million metric tons went through the PoR (Port of Rotterdam Authority, 2009). Every day enormous quantities of chemicals and other hazardous materials are imported, transferred and stored at the PoR. Handling such substances implies potential disasters for humans and infrastructure in the area. In addition, large-scale emergencies or crises call for the participation of several regional agencies, which may include police, port authority, medical services, fire department, hazardous materials experts, and government officials. An emergency may affect not just the PoR operations, but the whole logistics infrastructure of The Netherlands, Germany and other countries, as well as posing a threat to an area that is densely populated.

Rotterdam responds with a CoPI team and…

The Vignette in Chapter 1 already described the GRIP procedure for coordinating crisis response in The Netherlands. The CoPI team is a central aspect of this procedure and in the PoR typically includes fire, police, medical services and the port authority. Representatives from all disciplines gather inside a specially equipped vehicle to gain situation awareness, make decisions and provide operational leadership for the response, coordinating the activities within and between agencies. Typically, the CoPI team is setup within 10 minutes, then discussion starts and minutes later, when situational awareness is achieved, action is taken. Once action is underway, discussion restarts to revise the action plan.

a command structure.

Figure 3-1 shows the command structure for crisis response in the PoR, according to the GRIP levels. It shows a hierarchical relationship of command and control established from the bottom-up as the emergency escalates. It starts as the operational level with field agents from the Police, Fire Department, Medical Emergency Services (*Geneeskundige Hulpverlening bij Ongevallen en Rampen*, or GHOR), Rotterdam Port Authority (RPA) and the Rotterdam Harbor Master Division (*Divisie Havenmeester Rotterdam*, or DHMR). It is followed by a Command Place Incident (CoPI) team with representatives (leaders) from each of the divisions. At the highest level, a Regional Operational Team (RegOT) includes the regional officers from the different services and an officer from the Army. These teams communicate through a central control room.

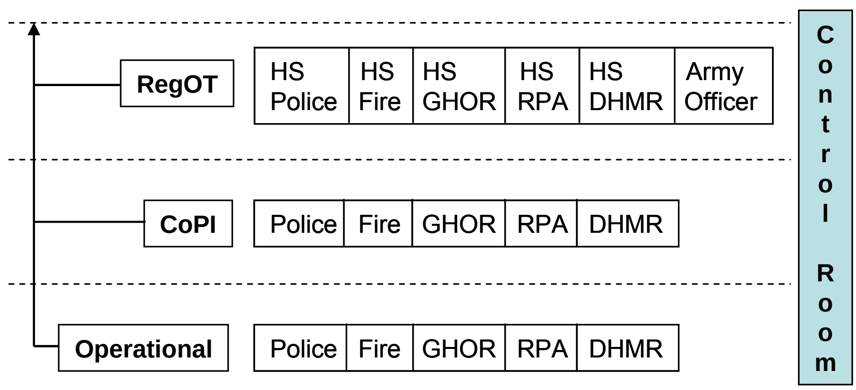


Figure 3-1 Command structure in the PoR

All emergency exercises that are part of the following case studies involved scenarios where the incident originated within the context of the PoR and for which a multidisciplinary response was necessary. Although the five exercises observed were different in size, they all included several physically spread responders, which is why the study was complemented with interviews, documents and discussions with other observers to supplement the limited point of view. The case studies were conducted mainly through direct observation. Since no video recording of the exercises was possible, the observations were written down in logs, some pictures were taken, and informal conversations were carried out with several responders, from police officers, to crisis managers, to exercise organizers, always depending on the proximity and willingness of these individuals and on the requirement for the observers to be unobtrusive.

3.2 Vignette: Introductory Field Notes

An enormous chaos. To an onlooker, there must have been something really wrong. Several fire trucks, police cars, and ambulances were parked next to a Hotel, just a hundred meters away from the entrance to a large industrial complex not far from where the River Maas (Meuse) flows into the North Sea. Firemen, policemen, medical emergency personnel, and hazmat experts were walking around in a hurry. A guest at the hotel came over with his dog and asked me whether he could go through and whether I knew what was going on. I tried to explain that it was just an exercise and that I thought he could go through as long as he didn’t cross the yellow tape. He said to me that it all looked like an “enormous chaos” and continued walking his dog with his attention on the responders and their vehicles. Later on, I observed a police officer being interviewed by the press (also part of the exercise): the journalist described the situation as an “enormous chaos” and showed special interest in the Dutch Royal Family, which was supposed to be involved in the fake explosion inside a cruise ship. When the interview was over, the police officer was excited and willing to share her feelings with me. I wandered how this chaos would look like in a real emergency and if people would react similarly.

Figure 3-2 Response boat from the PoR in the Maas River

See my vest. On the first exercise, I came physically close to the initial response as an external observer. One high ranking police officer looked at me taking notes and asked me whether I was from the press. Since I had no uniform, he automatically assumed this role for me. Indeed, being a civilian proved to be strange for some: more than once, responders (police above all, perhaps because they have been trained to be suspicious) would look warily at me and I was asked twice what I was doing there. Upon being confused with a journalist, my contact (a crisis manager from the Port of Rotterdam) provided me with an unaffiliated generic reflecting jacket, after which my presence was less notorious and allowed me to blend in as an unidentified responder. Wearing this jacket assigned me some role, instead of being “confused” with a civilian.

Figure 3-3 Participants during one of the exercises

Drop me a call. On one exercise, as soon as officers started arriving on the site of the incident, they met at the entrance of the industrial complex where the crisis had been designed to happen. Most appeared to stick to intra-agency communication (e.g. policemen would meet with policemen and firemen with firemen) whereas higher ranking officers would gather around separately among disciplines (e.g. police officer with fire officer). Once an initial assessment of the situation was discussed face to face, they (top-ranking officers) decided to set up a CoPI team inside the complex, prompting them to walk over to a trailer already placed there before the exercise. As I followed, I noticed one fire officer was carrying an open map, a folder with loose pages on it, a cell phone, a radio on his belt and a PDA in his jacket pocket (as he later told me). When he was folding the map on his way to the CoPI trailer, his cell phone fell to the ground and another officer behind him picked it up and handed it to him. The delay was only of a few seconds, but it involved two officers and drew the attention of several responders. The phone was OK, but it could have been damaged by the fall. One of the officers was walking next to me and pointed it out, saying that he wished some day soon all those devices (electronic or not) could be replaced by one PDA providing combined services.

Figure 3-4 Response vehicles in one of the exercises

Donuts, deaths and jokes. Because the exercises are in training mode, the mood can be more relaxed than in a real emergency, with some stress occurring around decision-making due to incomplete information or personal disagreements; and there is still a sense of time pressure which the organizers make sure to keep. However, tension dispels around mid morning when coffee, candy bars or donuts are passed around, creating an atmosphere which wouldn't intuitively be linked to an emergency. People will drop a map or a radio to grab coffee or leave the CoPI trailer to eat their donut. At one point, an officer jokes after a fake explosion has been announced: "Oh, poor X and Y have just died". This reminds a researcher that the situation is fictitious and should be perceived with a critical viewpoint. Nonetheless, the same officer later reminded me that during real emergencies they also eat and joke.

3.3 Coordination in Crisis Exercises: Case Study 1

The first set of exercises was used to study actual coordination practices and ICT use during crisis response. The conceptual background against which the observations are classified corresponds to the information-processing view of coordination presented in the previous chapter. The categories for kinds of dependencies and coordination mechanisms are used to classify coordination related findings together with the ICTs used to support them. The case uses the I-P coordination conceptual framework as a lens to study coordination practices during crisis response exercises both to add empirical content that exemplifies the framework's concepts and to contribute to the identification of its shortcomings and opportunities for extension or revision of the framework.

The first case study...

Setting and method of Case Study 1

This case study can be classified, following Yin (2003), as single-embedded and, following Stake (1995), as instrumental. It is single, as opposed to multiple, because it did not aim at generalizing new hypotheses or categorically contrasting cases, but rather at empirically confronting and enhancing existing theoretical notions; in this case, those related to the I-P view of coordination. The case is embedded, as opposed to holistic, because it involved multiple units of analysis in order to observe coordination issues at the horizontal (between responders) and vertical (hierarchical) levels. Finally, the case was also instrumental because the issues explored exceed the case exclusively, in opposition to an intrinsic case in which the aim is to learn only about the individual case. Once again, this stems from the assumption that learning about coordination in crisis response contributes to learning about coordination in similarly complex environments.

is single-embedded and instrumental,

The units of analysis investigated in this case study focus on the initial response phase, on professional first responders and on operational leadership. The emphasis on first response (as opposed to planning or recovery) is due to the fact that the exercises focused on training operational response during the first hours after an incident has occurred. The focus on first responders is based on the interest of observing inter-agency interaction on-site, when the crisis is of a scale or complexity that requires more than one discipline. Finally, looking at operational leadership allows observing vertical coordination (between hierarchical levels of a response organization), in addition to the horizontal coordination between the field responders and between the leaders.

focusing on 1st response / operational leadership.

First exercise: "Safe Harbour". This rehearsal had the main goal of performing a full-scale test of the new C2000 communication system (described later on). In it, approximately 300 people were participating around two incidents. On the first incident, the police were entrusted with crowd control due to hooligan activity on a ferry. Also, an explosion was supposed to happen and a real fire was staged as a result. Actors were hired to perform as either victims or hooligans to add realism. As part of the exercise, a simulation tool was used to support various processes and tasks in preparation, execution and evaluation. The unit of analysis was centralized command (a group of 15 operational leaders from different disciplines), rather than on-site response. The observation focused on radio and computer-based communication between responders and central

Sources of data include: observations of a set of….

command. In addition, some officers were in charge of checking the correspondence between the planned sequence of events and the events unfolding on site; talking to these officers during the exercise offered a global view of the central command with respect to on-site operations.

training exercises,

CoPI training exercises. Throughout these workshops, responders from the Fire Brigade, the Police, the Medical Services (GHOR), and other disciplines (hazmat, environmental, port authority and industrial representatives) exercised crisis response, focusing on the CoPI team. Two scenarios were designed for these exercises. One involved a fire in a ship, which included VIP personnel to add priority to the decision-making process. The other was an explosion at an industrial compound involving an important number of potential victims. Because the focus was on the CoPI team, GRIP level 1 was the focus, but escalation did occur until GRIP 2 to add complexity to the response. Some of the officers involved in the exercises were the same as the ones present in the first exercise, presenting the chance to come back to the same individuals for discussion. It was possible to observe the setup of the CoPI team (the decision to go to GRIP 1 when officers meet at the entrance of the industrial compound). In one of the exercises the focus was on the information manager to observe the use of the MultiTeam tool (described later on). In total, four sessions were observed. Questions were asked to a police officer, an information manager, a crisis manager from the port, and a port officer in charge of communications, all questions were improvised according to events in the exercise.

interviews and documents.

After the exercises, an additional semi-formal interview with a Crisis Manager from the Port (CMP) was conducted (anonymity was requested). This interview took place three months after the final exercise was observed and the logs had been structured according to the I-P view of coordination. The questions focused on coordination issues during crisis response in the port and the role that ICT has in supporting coordination. The CMP had the chance to review the transcription by e-mail and add a couple of comments to expand the answers. A final source of data was a set of documents related to crisis response in the Port. Of special interest were the GRIP procedure and the Crisis Management Plans of the Rotterdam-Rijnmond Region. In order to code the findings, the logs, interviews and secondary data were open-coded to label statements as potentially referring to coordination dependencies or mechanisms. After this general coding, tables were made to classify dependencies as either flow, fit or sharing, and mechanisms as either standard, mediation or mutual adjustment. Some coordination mechanisms that did not comfortably fit into those categories were placed separately and later labeled using some of the alternative views of coordination presented after the I-P view in Chapter 2. In terms of the technological support, the tools observed were classified according to the types of ICT support presented in Chapter 1.

Findings from Case Study 1

Observations in the form of log, photos, interview transcripts and manuals were classified according to the conceptual framework for the information-processing view of coordination (presented in Chapter 2). Since some of the ICT used supports coordination, the findings begin with presenting the use of ICT before going on to present the dependencies and coordination mechanisms.

Many ICT tools and applications are present in the Port of Rotterdam. In fact, some might argue that the myriad of systems, devices and information make integration and efficiency during the crisis response more difficult. For instance, the Vignette earlier in this chapter relates how the multiplicity in tools can become an inconvenience and how it prompts responders to wish for simplified and unified tools. The officer wishing to have a single PDA providing all the necessary services was voicing the concern that ICT can contribute to an increase in information processing needs, even if it is intended to provide information processing capabilities.

Findings indicate wide ICT use, including:

Of all the systems available, only a few where used frequently during the exercises (mobile phone and radio), while others remained secondary, despite their sophistication. One officer argued that regardless of which technology is in use, its adoption is conditioned by the fact that responders use it frequently. Indeed, that is one of the secondary objectives of some crisis response exercises: to acquaint responders with the use of crisis response technology. When asked about the ICT used during an emergency, as opposed to daily routine, a crisis manager from the Port pointed out that there is a difference on the ICT that responders use, but also in the type of work that responders do: "they are not used to sitting down and writing things in a computer". This reminds us of the situated approach discussed in Chapter 2, according to which technology cannot be fully understood in isolation, but requires considering the context in which the users adopt it, re-shape it and are shaped by it. Training and routine use should accordingly be an integral part of this adoption. Besides the widely used radio and mobile phones, some of the ICT systems used during the exercises include:

The C2000 (Vts Politie Nederland, 2010) communication system offers inter-agency communication services over a digital radio network supported by a fixed backbone. The goal behind C2000 is to replace the heterogeneous array of analogue communication networks used by the different response agencies in The Netherlands with a shared digital network that should enable a more integrated, faster and noise-reduced connectivity. Part of the motivation for using C2000, which is related to coordination, is offering a standard way of communicating for all response agencies to avoid problems of coverage, channels or lack of inter-communication possibilities. The main components are walkie-talkies and car phones, along with gateways to link to the phone network. During the exercises, it was used for exchange and broadcast of emergency-related information.

telecommunication,

The MultiTeam (HAN Dataport Benelux, 2010) system has been developed on the basis of the GRIP levels described earlier. All available MultiTeam modules form an integrated process for coordinated disaster management. MultiTeam supports different agencies by exchanging messages and documents through contact lists and with links to other applications (e.g. GIS). Within the case exercises it was only used in two occasions, although it was always enabled and ready to use. According to an agent acting as information manager, the value of MultiTeam is that it has been agreed upon by all agencies in The Netherlands (thus becoming a semi-standard).

integrated systems,

Geographic information technologies (GITs) are a fundamental part of modern crisis management. Their ability to represent the affected area and enable information sharing to reach common awareness is widely recognized. In *geographic information technology,*

Rotterdam, while there is not yet a single geographic information system (GIS) for all agencies, they use sophisticated maps in the Port Authority to track vessels, containers and harbor elements. This is coupled with other data concerning population, weather, gas clouds, among others, which is useful during an emergency. In the first exercise, a GIS was used to show interactive information around the incident area. A crisis manager from the port said "when you visualize it, you don't need to communicate about it". It should be noted, however, that there was heavier use of paper maps (inside the CoPI vehicle at least) than of GIS.

workflow technology and simulation.

The CrisisSim (E-semble, 2010) system supports preparation, management and evaluation of command posts or live exercises. Checklists are created digitally during preparation, scripting and observation. During one exercise, CrisisSim was used to manage the storyline (of the crisis script) by sending event triggers to participants and instructing the exercise staff at remote locations. Observation results are collected digitally during the exercise through an Observation Module. After the exercise, the Evaluation Module offers review functionality. Simulation with CrisisSim was used in the first exercise as a "kind of document workflow", according to a Port Officer, which allowed controlled enactment of the scenario.

Non computer-based technology…

Besides computer-based technologies, other tools support the response, such as: maps, boards, meeting rooms and trailers. Maps (diagrams or aerial photos) were heavily used to draw out response strategies inside the CoPI vehicle and point out emergency-related information (response units, gas clouds, evacuation routes). During the exercises, maps of the Rotterdam Port and of the industrial facilities in particular were used. The leaders would draw or write on the maps to plan entry routes for responders, evacuation routes for victims, placement of response units, placement of victim collection points and potential risks attached to the industrial facilities.

is also widely used.

Acrylic and paper boards were also used inside the CoPI to scribble down the facts of the emergency and the response actions. One board used a pre-existing pattern to divide facts into types around the central incident, such as: press, victims, and organizational facts. Some facts that did not fit into the categories were placed on the unlabeled categories. Clogging, overwriting, poor handwriting and lack of recorded facts were obvious shortcomings observed in the exercises. In one exercise, the same paper board was used in two subsequent exercises, showing the data from the previous training effort to the new response team.

The CoPI vehicle is the main on site coordination, command and control center. It is the place where the CoPI team is formed (close to the incident, but not so much to reduce the risk of being affected). A problem with the trailer is the size. During the exercises, some individuals were left standing at the entrance and some were not even able to listen to the discussion. One officer complained that ventilation was required, as the air quality became unbearable when the CoPI was fully packed. On one exercise, access the CoPI was limited by putting red tape around it (so that no one would enter before the CoPI was setup) and later on shutting the door (preventing access from non-CoPI personnel). Figure 3-5 contains a photo of the outside of the CoPI vehicle showing how full it can become. Figure 3-6 shows the CoPI inside where the use of maps and boards is active, although there is also a laptop enabled for GIS and MultiTeam.

Figure 3-5 CoPI vehicle from the outside

Figure 3-6 CoPI vehicle inside

Other findings are classified into:

Other findings are classified according to the I-P view of coordination. While the findings do not exhaustively represent all possible dependencies, they illustrate the I-P view and its limitations. The labels for each dependency and mechanism are accompanied by the tag used in Figure 2-1. Thus, D1, D2 and D3 correspond to the flow, fit and sharing dependencies, while M1, M2 and M3 correspond to standards, mediation and mutual adjustment coordination mechanisms, respectively. Some findings do not fit comfortably into those categories, prompting the use of some alternatives (i.e. practice-based and role-based coordination). This also indicates that the classification is based on similar efforts (e.g. Shen & Shaw, 2004) and on discussion with other researchers, but is not meant to be definitive, rather illustrative of real coordination practices and the benefits and limitations of using the I-P view for analyzing them. Table 3-1 shows findings related to flow dependencies and their coordination mechanisms.

Table 3-1 Flow dependencies (D1) found in the exercises

Flow Dependency	Coordination Mechanism
Information flows: Information is generated by events or by agents participating in the response. Not all agents have access to all information at the same time, which is why information must flow from a producer to a consumer. Message content included: incident reports, queries and decisions to be distributed. Information flows occurred within: voice communication, radio, phone, the C2000 system, e-mail, and the MultiTeam system.	Mediation (M2). Broadcast: radio and MultiTeam use it to distribute queries and decisions top-down.
	Mediation (M2). Command and control hierarchy: In the GRIP response procedure, information flow arrows indicate how response units should handle communication lines hierarchically. Information is supposed to flow upward, decisions downward.
	Mutual adjustment (M3). Mixed media: in one exercise an e-mail query was sent by the information manager (IM) through MultiTeam, prompted by a face-to-face question from an officer. Later, the reply was received directly by the officer through the radio.
	Mediation (M2) / Role-based: the IM role is responsible for feeding and reviewing the systems inside the CoPI, unloading the team of information retrieval tasks. This often means that the CoPI members will use the IM in mediating information flows without necessarily specifying where these flows should start or lead to. Accordingly, the IM also needs to figure out the roles that make up the sources or destinations of relevant information; using MultiTeam might contribute through mailing lists or expertise linked to registered users.
Task flows: Some response tasks are prerequisite of others and so must be carried out in a certain order. In the exercises, task flows differ from those in a real emergency, because some managers know how the incident will develop.	Standard (M1). Simulated workflow: In the first exercise, the incident events were planned in detail and executed with the aid of a simulator.
	Standard (M1). Written scripts: In the CoPI exercises, two scripts guided the events. The scripts were basically spreadsheets with events relevant to the different agencies, color coded according to discipline (red-fire, blue-police, green-medical).

Flow dependencies represent resource flows between activities. The two flow dependencies identified in Table 3-1 are information flows and task flows. Information flows help identify one of the direct sources of ICT support, while task flows are the most common form of flow dependencies. It should be noted, however, that task flows are subject to standard or planned coordination mechanisms, precisely because the crisis exercises have been planned for, reducing uncertainty. Nonetheless, exercise organizers artificially create uncertainty by changing the order or timing of the planned crisis events, or by improvising new information items, prompting an equally improvised response. The flow dependencies listed in the table are managed by two standard coordination mechanisms, three mediation coordination mechanisms, one mutual adjustment mechanism and one role-based mechanism (which is outside the I-P view, as argued in Chapter 2). The next set of findings in Table 3-2 contains examples of fit dependencies with the coordination mechanisms used to manage them.

flow dependencies,

Table 3-2 Fit dependencies (D2) found in the exercises

Fit Dependency	Coordination Mechanism
Decision-making: Decisions need to be made quickly, under pressure and with limited information. Often, they must be made between more than one agent, since actions will affect the response network and the incident itself. Decision-making inside the CoPI is a group effort, but is the responsibility of the Operational Leader. Once situational awareness is reached and first actions are put in effect, they restart discussions to reassess the situation and revise the action plan.	Mediation (M2). Centralized decision-maker: Decision-making inside the CoPI was a group effort, but was ultimately the responsibility of the Operational Leader. Also, if the GRIP level reaches 4 the incident has extended beyond a single municipality. Decisions would affect a broader area and have to be made by more than one mayor (advised by senior officers). This results in the need for one of them (usually the mayor from where the incident started) to become Coordinating Mayor.
	Mutual adjustment (M3). Feedback: Inside the CoPI, officers make decisions using centralized means such as a leader and a whiteboard, but they adjust their awareness of the situation by learning from each other the details of the incident, often resulting in a new understanding of it.
	Practice-based: the Fire Chief is the leader by default. However, the coordination structure may be altered when different expertise is required (e.g. a chemical expert may start as observer and end up leading a decision if a toxic gas cloud forms).
Public information: An important aspect of the response is how the response team will communicate with the press and the public. This requires determining what to communicate, to whom, when, and how (which medium).	Mediation (M2). Single informant: All GRIP levels specify a single informant, typically from the Police, as liaison with the press.
	Mediation (M2) / Standard (M1). Broadcast: if information needs to be pushed to the public, rules are applied for broadcasting through: TV, radio, SMS, Teletext, Call center.

Table 3-2 Fit dependencies (D2) found in the exercises (continued)

Fit Dependency	Coordination Mechanism
Situation assessment: This dependency relates to the fit of multiple agents coming up with a single picture of the incident stemming from different points of view, levels of expertise and priorities.	Mediation (M2). Master/slave users: A geographic information system (GIS) system was used to contribute to a single visual representation of the incident. The information manager was master user in the CoPI and the Central Command users were slaves (no updating).
	Standards (M1). Standard icons and labels: In the GIS, standard icons can be used to describe incident related information reducing ambiguity. For example a flame icon can be used for a fire, see for instance (Fitrianie, Datcu, & Rothkrantz, 2007). In the same way, MultiTeam provides a limited set of standard labels for describing an incident, called SITRAPs, or Standardized Situation Reports.
	Role-based: roles (and rank) are recognized through the network of acquaintances, through uniforms and through profiles and labels in MultiTeam, contributing to a quicker assessment of the organization based on widely-understood symbols.

fit dependencies,

Fit dependencies refer to multiple activities producing a single resource. In Table 3-2, multiple responders at different levels must come up with a single decision, a single information report to the general public, and a single assessment of the situation to enable a shared mental model and a common operating picture. These dependencies are managed with two standard coordination mechanisms, four mediation mechanisms and one mutual adjustment mechanism. Outside the I-P view, the table shows one practice-based and one role-based coordination mechanism. This leads to the last kind of dependency in Table 3-3: resource sharing, which is placed next to each of the corresponding coordination mechanisms found.

Table 3-3 Sharing dependencies (D3) found in the exercises

Sharing Dependency	Coordination Mechanism
Communication channels: Crisis response is a communication intensive effort with limited channels (capacity and bandwidth). All ICTs are subject to shared bandwidth and capacity limitations.	Mutual Adjustment (M3). Simultaneous sequencing and prioritizing: C2000 or radio users shared a limited amount of communication channels. As expected, they had to take turns speaking, but also had a red button available on the device for gaining priority access to dispatch.

Table 3-3 Sharing dependencies (D3) found in the exercises (continued)

Sharing Dependency	Coordination Mechanism
Physical resources: The same resource may have to be used in different locations or by different agents and disciplines. Assignment of units, vehicles and other material is shared within the response and with other users outside the incident. For example, access and use of the CoPI trailer was shared.	Mediation (M2). Access priority: In a few exercises the CoPI trailer was so full that some participants had to stand outside. For subsequent exercises they restricted access (only leaders) to prevent overcrowding.
	Mutual Adjustment (M3). Feedback: On one exercise initial negotiated resource assignment was changed after officers learned that VIPs were involved, changing the incident from regional to national interest.

The resource sharing dependency is about two or more activities sharing the same resource, often due to limitations in availability or accessibility, despite the fact that in this case some resources have been made available prior to the beginning of the exercises in anticipation and preparation – and due to the fact that several groups of responders have to attempt a response for the same situation, reusing the same vehicles, trailers and devices used by previous groups when the exercises are sequentially enacted. In Table 3-3, resource sharing is exemplified through sharing of communication channels and physical resources. The table shows one mediation coordination mechanism and two mutual adjustment coordination mechanisms.

and sharing dependencies.

Discussion of Case Study 1

The findings of this case study were classified through the application of the conceptual framework for the information-processing view of coordination presented in Chapter 2. Types of dependencies (flow, fit and sharing) proved to be an appropriate starting point for the study of coordination. With regards to the kinds of coordination mechanisms (standards, mediation and mutual adjustment), the classification process was not equally straightforward, as in some cases a specific mechanism could be classified in more than one approach. For example, the information manager sometimes acts as a mediator, while at other occasions contributes to coordination in a more role-based manner (see Table 3-1). Similarly, the broadcasting mechanism for public messages follows both a standard and a centralized mediation approach (see Table 3-2).

Discussion points of the case:

Mutual adjustment as a type of coordination mechanism also exhibited some ambiguity. While it can be used directly to classify coordination based on feedback (as in Table 3-2 and Table 3-3), it was also used to label more emergent kinds of coordination. In one instance (see Table 3-1) it is used to label a series of messages exchanged between various responders using different media. This example suggests emergent behavior which goes against the standard expected procedure and uses both centralized systems and boundary spanning lateral relationships. A face-to-face query was posed out of physical proximity between a

mutual adjustment,

medical officer and the information manager (IM); this was transformed into a written e-mail query sent by the IM to a list of users in MultiTeam. The exercise finished without the message being replied to. The IM was asked about this, to which he replied that there had been an answer, except it was sent directly to the medical officer through radio (enabling others to listen in as well). The original question was posed by the medical officer in order to determine whether the incident involved some chemical hazard that would require the medical emergency personnel to wear protective gear. Although the reply from a field officer eventually reached the medical officer, it used three different media and no record was left on MultiTeam as would be expected.

granularity of coordination mechanisms,

This last example might indicate that there is an issue of granularity to be taken into account when classifying coordination mechanisms (meaning that one coordination mechanism can actually be sub-divided into smaller components that may correspond to different types). It also points to a general problem with using taxonomies in that it can force the placement of an instance within the dominant category, while hiding the less prominent characteristics that may indicate a different class. But most importantly, perhaps, it illustrates the limitations of the I-P based view which pays too much attention on information exchanges and not on the situated uses of technology or on the aggregate effects of combining coordination mechanisms.

mediation,

As expected from the command-and-control approach to crisis response in the exercises, findings suggest that *mediation* was the preferred type of mechanisms for coordination. Although the case study is not amenable to quantitative analysis, it is still clear that most mechanisms (8 in total) are classified as mediation or hierarchy. In fact, one of the crisis managers emphasized command over coordination and defended hierarchy by saying that "people usually stay within recognized structures…hierarchy is clear to them. Furthermore, people should communicate within their own key service (people they know) so that there is no room for hesitation." When pressed to address this issue, a crisis manager went so far as to say that besides hierarchy and standards there was no other way to coordinate the response. This is indicative of the emphasis that both crisis response and the I-P view of coordination place on hierarchy for coordination and suggests that it can not only influence the way in which ICT is designed and used but also the worldview of the professionals managing such technology.

and ICT use.

With respect to the role of ICT, the case study findings support the claim that ICT can contribute to the fit between coordination dependencies and mechanisms, keeping in mind that ICT can increase information needs and not only capabilities, and that the same ICT tool can be used to support different mechanisms. It also appears that most ICT reflect the preference on mediation and standard coordination mechanisms, but this could of course be a reflection of a preference of the responders, rather than something forced by design. For example, the use of GIS can contribute to collaborative construction of an operational picture of the crisis, but choosing a master/slave configuration for the users (as seen in Table 3-2) imposes a centralized hierarchical restriction on the use of the system that helps in avoiding conflicting views but also assumes that the centralized master will have the "best" view of what is going on.

3.4 Coordination and Information Quality in Crisis Exercises: Case Study 2

Besides coordination, effective crisis response also requires access to the right information at the right time. Such requirements depend on information quality (IQ) dimensions, such as correctness, accuracy and timeliness. Multiple reports on crisis response have argued that lack of information quality is a problem in practice (Dawes *et al.*, 2004). The main premise of the second case study is that effective coordination depends on high IQ across multiple information management activities. This means that having access to high quality information, and appropriately distributing or sharing this information between the agencies, improves the conditions for effective and efficient coordination. However, despite the multiple contributions on defining IQ (Fisher & Kingma, 2001; H. Miller, 1996) we still do not fully understand the relationships between IQ and coordination. Accordingly, this case study addresses this relationship through information management activities in order for coordination to be more systematically related to ICT support. The goal of this case study was to identify hurdles for information quality as potential sources for improving coordination during a crisis response. This contributes to complementing the empirical data beyond the existence of coordination dependencies and mechanisms to information quality problems that may be amenable of improvement in order to provide additional support for coordination with ICT.

Coordination is tied to information quality,

Setting and method of Case Study 2

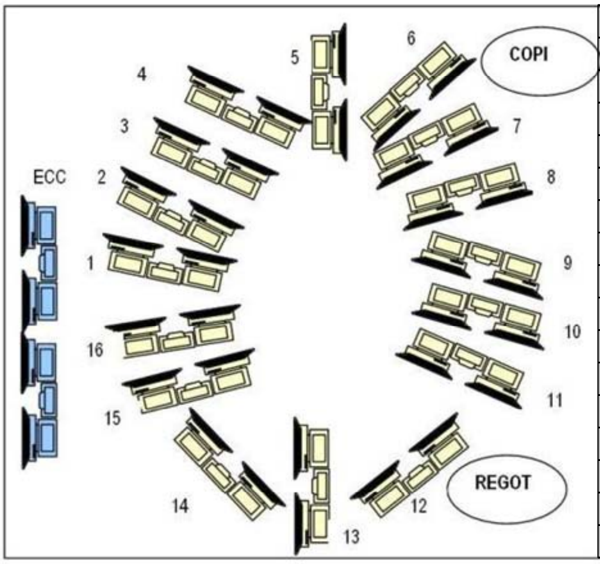
The case study was instrumental as it was selected for its ability to contribute to understanding of an issue or refinement of theory (Stake, 1995). More specifically, it illustrates some of the information quality problems and coordination challenges during interagency crisis management. The crisis response exercises observed were organized indoors for three days, containing three rounds per day. The objective was formulated by the organizers as: "Introducing advanced information systems to relief workers, including commanders of the relief organization that participate on the decision making levels of disaster response." Table 3-4 provides an overview of the elements.

as the 2nd instrumental case study illustrates.

Table 3-4 Elements of the exercises in case study 2

Focus	Collective response to crisis using advanced ICT tools
Crisis management Levels	Operational level (first responders), tactical level (COPI), strategic level (ROT) and Emergency Control Center
Participating agencies	Police, Fire and Medical Services, DHMR (Division Harbor Master Rotterdam), CVD (Center for public service)
Setting	Computer aided simulation, Indoors
ICT Tools	ICIS, CeDRIC, GROOVE

The emergency scenarios that were used during the two rounds of exercises followed basically the same pattern, with the exception of three variable elements: the location, the magnitude and the information structure. The main incident was the collision of two ships: a container ship and a passenger ship, which results in an explosion inside the first. Because of the potentially hazardous chemical material on the container ship there is a risk not only for the passenger ship, but also for the neighboring ships and factories in the busy setting of the PoR, thus the response requires multiple disciplines from professional emergency agencies, advised by domain and port experts. The entire exercise was conducted in one room, in the centre of which a beamer/screen was set up, allowing for collective explanation and evaluation of the exercise. Figure 3-7 provides an illustration.



Nr.	Emergency Service
1	Leader RegOT (Regional Operational Team)
2	Spokesperson CoPI (Commando Place Incident)
3	Information Manager CoPI
4	Chemical Advisor CoPI
5	DHMR (Division Harbor Master Rotterdam)
6	CvD (Center for Public Service)
7	Police Officers for CoPI
8	OD Fire Department
9	Leader CoPI
10	Spokesperson RegOT
11	Information Manager RegOT
12	Chemical Advisor RegOT
13	HS DHMR
14	HS Police
15	HS GHOR
16	HS Fire Department

Figure 3-7 Schematic overview of exercise setup

Sixteen workplaces circled the center of the room. The numbers at each workplace represent an agency participating in the exercise. Each workplace represented an actor and contained two PC's and a printer. Each actor was represented by one or two persons. It is clear from those involved that the team inside the observed setting was the emergency control room, the CoPI and regional command, while operational actors were external.

Current literature on interagency disaster response considers the issues of coordination challenges (Chen *et al.* 2008), and information quality (Fisher & Kingma, 2001) separately (albeit, sometimes highlighting the importance of information management for coordination). As a result, coordination challenges and information quality dimensions may be linked together through information management activities. The information quality attributes and the list of coordination challenges used in this case are not meant to be exhaustive or comprehensive, but rather suggestive of the kinds of issues and elements related to coordination and information quality. The link through information management activities addresses this relationship. The case starts from the claim that those information management activities, when carried out with information quality, constitute mechanisms for tackling coordination challenges.

This relationship between coordination and information management is illustrated using this case study. A table was created linking information quality attributes to information management activities, where each cell contains an information management activity that coupled to an information quality attribute contributes to dealing with a particular coordination challenge (the concepts and resulting table are presented in the next section). The case findings present the observations of a total of 6 crisis response exercises. Using the table as observation protocol, events and issues were registered after the exercises. This was done by two separate researchers independently and then discussed using crisis response documents from the PoR and the Rotterdam-Rijnmond Region. The coordination challenges and information management activities were rated in a three point scale, based on frequency and/or intensity observed, in order to place emphasis on those issues that showed the most opportunity for improvement. The units of analysis during the exercises were the information manager and the Emergency Control Room (ECR) of the crisis response organization of the Port of Rotterdam. Observations inside the ECR included different stakeholders comprising multiple response disciplines and three hierarchical response levels (operational, command and regional levels).

Data collection and analysis is based on:

The rest of the study proceeds by presenting how the connection between coordination and information quality was established and then continues to show the findings that used the resulting table as a lens for classifying the observations.

Linking information quality to coordination

In Chapters 1 and 2 the challenges of coordination in crisis response and the I-P view of coordination have already been discussed. This case study uses a single source of coordination challenges to develop the connection with information quality. The coordination challenges (C) addressed in this case study are expressed in Table 3-5.

coordination challenges,

Table 3-5 Coordination challenges in crisis response (Chen *et al*. 2008)

C1	High uncertainty, sudden and unexpected events
C2	Risk and possible mass casualty
C3	Increased time pressure and urgency
C4	Severe resource shortage
C5	Large-scale impact and damage
C6	Disruption of infrastructure support
C7	Multi-authority and massive people involvement
C8	Conflict of interest
C9	High demand for timely information

information management activities,

The previous coordination challenges are related to an information-intensive domain and dealing with them often depends on effective information management, understood here as finding, integrating and sharing information. Achieving coordination between a disparate group of actors depends on their access to timely, valid information and their capacity for information search, exchange, absorption and adaptation (Comfort & Kapucu, 2006). However, this capacity is limited in humans: as information requirements increase, cognitive capacity decreases (Galbraith, 1974). Accordingly, information management (IM) activities can be deployed to deal with this limitation. This case study considers three basic information management activities for crisis response (Comfort, Dunn *et al.*, 2004; Heath, 1998; Stephenson Jr, 2005) shown in Table 3-6.

Table 3-6 Information management activities in crisis response

IM1	Searching, collecting and gathering information about the incident
IM2	Collating, evaluating and analyzing the information gathered
IM3	Distributing, sharing and exchanging incident related information

These information management activities need to be carried out within the complex and dynamic setting of crisis response. This imposes particular considerations for them to be successful. Some of these considerations are:

- IM activities should be carried out both within and across agencies (Heath, 1998).
- IM activities need to be deployed within an information infrastructure that is both flexible and ordered (Comfort, Dunn *et al.*, 2004).
- IM activities should focus on the core information of the incident (Comfort, Ko *et al.*, 2004).
- People and groups need to share interpretation schemas, or at least be able to make conjectures about what other people's schema is (Cuel & Cristiani, 2005).
- IM activities should be carried out as much as possible before the actual crisis occurs (Bui & Tan, 2007).

and information quality.

During the process of interagency crisis response, information is considered to be one of the essential needs of relief workers and poor information quality (IQ) can be disastrous for both relief workers and victims (Fisher & Kingma, 2001). Emergency managers have learnt that accurate and timely information is as crucial as is rapid and coherent coordination among the responding agencies (van de Walle & Turoff, 2007). Moreover, because disaster management agencies are information- intensive, their effectiveness largely depends on the information they have available. IQ is a multidimensional concept, describing properties of the information received, capturing a wide range of variables such as accuracy, timeliness, completeness, consistency, relevance and fitness for use (Wang &

Strong, 1996). Miller (1996) adds format, compatibility, security and appropriate amount of data as important variables for measuring the IQ. Table 3-7 lists some of the IQ dimensions and related problems pointed out in literature.

Table 3-7 Information quality (IQ) attributes and exemplary problems in crisis response

(IQ1) Accuracy	In emergency management, information about technical conditions may be ambiguous and unreliable (Kontogiannis, 1996).
(IQ2) Timeliness	In analyzing an emergency, the situation changes over time so it is very important to know the order of events and their cause-effect relations (Atoji *et al.*, 2000).
(IQ3) Relevance	Certain events viewed in isolation may appear irrelevant or benign in terms of the emergency, but when analyzed collectively may identify a potential threat (Adam *et al.*, 2007).
(IQ4) Quantity	When a large-scale disaster happens, a great deal of information occurs in a short period of time (Atoji *et al.*, 2000), resulting in too much information to process (Jenvald *et al.*, 2001) and straining the capacity of the management and communication systems (Manoj & Hubenko Baker, 2007).
(IQ5) Completeness	There are potential delays influenced by the availability and dispatch of complete information about the incident (Chen *et al.*, 2005).
(IQ6) Format	To enable information sharing, document type definitions have to be in a well-defined format. While the format of data is arbitrary, the format of data definitions needs to be rigorously defined (Jenvald *et al.*, 2001).
(IQ7) Security	Sharing information during an emergency is challenged by trust and security issues (Manoj & Hubenko Baker, 2007), because of the need to protect potential misuse of information; however, excessive regulation hampers responders from getting useful information from other agencies (Kim *et al.*, 2007).
(IQ8) Consistency	If several information systems suggest different location coordinates, this inconsistency delays decision making (Fisher & Kingma, 2001).

The above information quality dimensions, coupled with information management activities in order to deal with coordination challenges become the core of Table 3-8 that matches information management activities (IM1, IM2 and IM3) with the IQ dimensions (IQ1 to IQ8). This was done to present some potential benefits for coordination that can be achieved when carrying out each of the IM activities with IQ criteria. These example benefits are at the intersections of IQ and IM in the table, based on interpretation of the literature prior to the exercises.

Table 3-8 How information management activities supporting information quality may contribute to dealing with certain coordination challenges

IM activities / IQ dimensions	(IM1) Search, collect and gather incident information.	(IM2) Collate, evaluate and analyze the information gathered.	(IM3) Distribute, share and exchange incident related information.
(IQ1) Accuracy	Finding accurate information is critical for assessing the potential risks of the incident (C2).	Evaluating information for accuracy contributes to better allocation of limited and distributed resources (C4).	Exchanging accurate information helps determine the scale of impact and damage (C5).
(IQ2) Timeliness	Quick information gathering is critical in dealing with a dynamic setting and time-pressure (C9).	Integrating and analyzing incident information with time-related data, helps create a cause-effect picture (C1).	Distributing the information in a timely fashion to responders improves awareness of each others' activities and decisions (C9).
(IQ3) Relevance	Retrieving relevant information about the incident reduces the uncertainty (C1).	Evaluating the relevance of information contributes to improving speed and certainty (C1).	Distributing relevant information to each different agency, contributes to faster decision-making (C3).
(IQ4) Quantity	Collecting sufficient information from all agencies helps in common situation awareness and goal agreement (C8).	Filtering the information from multiple wide-spread sources helps prevent information overload (C5).	Distributing the right amount of information to the right people helps deal with an increasing demand for information (C9).
(IQ5) Completeness	Gathering complete resource availability information contributes to improved resource usage (C4).	Evaluating for completeness contributes to better assessment of risks (C2).	Distributing complete incident information reduces the consequences of communication breakdowns (C6).
(IQ6) Format	The ability to gather information from different sources and in different formats improves redundancy of communication channels (C6).	Integrating information from different formats helps create a common picture and overcome technological differences between agencies (C7).	Distributing information in the right format for different responders contributes to dealing with the heterogeneity of agencies (C7).
(IQ7) Security	Enabling security in information retrieval prevents conflicts of interest from occurring (C8).	Analyzing security and privacy issues of data helps determine priorities and distribution (C7).	By preserving security, agencies will be more willing to share information (C8).
(IQ8) Consistency	Collecting consistent information speeds up awareness and decision-making (C3).	Evaluating information for consistency helps integrate the different sources from different agencies (C7).	Ensuring consistency in distributed information prevents conflicting decisions and action (C8).

Table 3-8 links information quality to certain coordination challenges through information management activities that can be implemented for crisis response. However, using the table requires taking into consideration the relationship that exists between these activities and the potential tradeoffs between them. Firstly, IQ dimensions should be an integral part of the whole information management system used during a crisis response, but the complete system would include remote sensors, public sources of news, and ad hoc responders, among others, over which there might be little or no control. Secondly, the table does not unveil potential tradeoffs involved in dealing with one information quality dimension over another. These tradeoffs need to be balanced and weighed against other information systems design principles, although this exceeds the goal for this particular case study. For example, some of the tradeoffs involved in the fifth row of Table 3-8 include:

There are tradeoffs between…

- Collecting complete information from all response agencies (IM1-IQ5) to contribute to a shared situational awareness of the incident may also impact the information-processing capacity, conducing to potential overload (IQ4);
- Evaluating and analyzing information that is as complete as possible (IM2-IQ5) may improve the assessment of risks related to the incident, but it may also increase the time for decisions to be made and communicated (IQ2); and
- Distributing complete information (IM3-IQ5) may reduce the impact of communication disruptions, but it may also require providing more information than is strictly relevant for a given agency or responder at a given time (IQ3).

information quality attributes.

The following sub-section presents the findings from the case study classified according to the previous table linking information management activities (which support information quality attributes) to coordination challenges.

Findings from Case Study 2

The observations recorded during the exercises focused on hurdles that challenged the level of information quality for responders at the command level, as well as on instances of general crisis response coordination challenges as observed during the exercises. The observations, firstly, illustrate the relationship between information management and coordination with the case observations and, secondly, point at sources for improvement through information management services that address information quality attributes. Although the focus was on the command and leadership inside the exercise setting presented in the last section, information was flowing both towards and from the operational responders not physically present at the room.

Case findings include:

Improving coordination is one of the goals of crisis response exercises (e.g. through training and networking). But the exercises themselves also allow for detection of coordination challenges for the response organization. The level of the coordination challenges observed is rated on a three point scale (low, medium and high) and is shown in Table 3-9.

coordination challenges,

Table 3-9 Findings on coordination challenges

Coordination Challenge	Level of coordination challenge observed
(C1) High uncertainty, sudden and unexpected events	High: The scenarios of the exercises contained both the element of surprise and unpredictability, making it difficult to predefine information needs and coordination activities.
(C2) Risk and possible mass casualty	High: risk in terms of uncertainty about the dangers was dominant in the first phases of the response.
(C3) Increased time pressure and urgency	High: the time pressure was very high especially since the exercise time was short and the events occurred rapidly.
(C4) Severe resource shortage	Low: the port area is known for having sufficient resources for handling at least one crisis at a time (this may be a problem in case of multi-event or distributed crisis)
(C5) Large-scale impact and damage	Medium: The scale of the disaster can be rated as medium because it was more a regional than a national issue.
(C6) Disruption of infrastructure support	Low: in general there was no notable disruption of the infrastructure during the exercises (the exercises were conducted indoors). However, had it been a real emergency, any disruption of the PoR affects critical infrastructure.
(C7) Multi-authority and massive people involvement	Low: As the observed case data is from an exercise, the number of agencies and decision making levels were limited.
(C8) Conflict of interest	Low: despite their different expertise and work processes, the agencies were each committed to jointly reducing casualties and mitigating the effects.
(C9) High demand for timely information	High: especially in the first minutes after the crisis is announced, there is a high demand for situational information coming from each agency.

information quality issues, and

In the current information architecture of the PoR there are multiple information managers, including a remote emergency control room, that have access to and share information with relief workers. In this case study, the focus was the CoPI information manager. As the disaster evolves and the complexity (in terms of amount of actors and necessary interactions) increases, more variations in the IQ were found. Because these variations are difficult to measure and quantify, Table 3-10 provides an overview of exemplary IQ issues, from the point of view of the information manager, for illustration purposes and not as an exhaustive list of information quality observations.

Table 3-10 Findings on information quality issues

IQ dimension	Observed IQ issues
(IQ1) Accuracy	In one exercise the initial coordinates of the ship collision were incorrect, leading to the concentration of field units in an area opposite to the real location.
(IQ2) Timeliness	The blueprint of one of the ships contained necessary information for firemen who had to go on one of the ships to mitigate the effects of the explosion. Getting access to the blueprint took about 20 minutes.
(IQ3) Relevance	Field units from the medical services were fed with information about climate conditions at the location, while they were far more interested in information about the victims.
(IQ4) Quantity	While incident information is scarce during the first 20 minutes of the exercise (low quantity), relief workers are overloaded with information from various sources with different quality values (high quantity).
(IQ5) Completeness	Information in the first 20 minutes of the crisis is incomplete during each exercise round, for instance about the number of victims on board.
(IQ6) Format	The blueprints of the ships are unavailable in digital format and need to be retrieved at a physical location.
(IQ7) Security	Access to information about potentially flammable materials stored in containers at the collision area is secured and not directly accessible.
(IQ8) Consistency	The members of the various agencies started with different information on the exact location of the incident.

Having observed information quality issues and coordination challenges, the next step is to identify information management activities that could be carried out or improved across the different information quality dimensions, in order to deal with the coordination challenges. Table 3-11 presents our observation about the IM activities conducted at the two units of analysis: the information manager and the Emergency Control Room. As with the coordination challenges, once again the issues are rated as low, medium or high. This indicates how intensive the information management activity was at the given level, providing a hint as to those activities and levels were ICT support could make a contribution. Thus, if the information management activity is rated as low, this means that there is a wider margin of improvement, than if an activity is rated as high.

information management activities.

Table 3-11 Findings on information management

Unit of analysis	Information Manager	Emergency Control Room
(IM1) Searching and collecting	Medium: the information manager depended on the available tools which only allowed for the retrieval of Geo data and mailing.	Medium: The ECR basically only pushes incoming information from different sources to field units
(IM2) Collating, evaluating and analyzing	Low: Apart from the background of the Information manager (expert) there were no specific protocols for information quality assessment	Low: The focus of the ERC is primarily information push and pull without information quality assessment
(IM3) Distributing, sharing and exchanging	Medium: The information manager only shared when asked by the head of the decision making unit	High: Filtered by the agency type represented in the ERC, information is distributed regularly to all relief workers.

Table 3-11 shows that both the Information Manager and The ECR primarily focus on sharing the information provided by the information systems they have access to. In this setting there is no predefined and exercised protocol for evaluating the quality of the information shared. Moreover, the current information systems used do not provide any services to support rapid IQ assessment. By supporting information management activities at the two units of analysis, considering the information quality issues (Table 3-10), an improved management of coordination challenges (Table 3-9) could be possible.

Discussion of Case Study 2

Discussion points of the case:

The second case study investigated the relationship between coordination challenges and information quality during interagency crisis response. This was motivated by the observation that in crisis response failure and success of coordination are often attributed to information quality issues. The findings support the initial argument that poor information quality can result in coordination problems. Conversely, they support the claim that by designing computer-based information management services that embed information quality dimensions we can improve coordination of interagency crisis response.

coordination challenges,

The coordination challenges that surfaced most strongly during the exercises were uncertainty, risk, time pressure and demand for timely information. There is a direct connection between the uncertainty created by sudden and unexpected events to the rest of these challenges. The risk for responders and civilians is greatest under high uncertainty which disables proper risk management by presenting multiple possible scenarios that cannot be discarded. This puts pressure on the crisis managers to deal quickly with abnormal situations and mitigate the effects of sudden harmful events. To do this, both responders and managers constantly require timely information. Although this suggests timeliness as a key information quality attribute during crisis response, considering the other attributes contributes to highlighting the importance not only of quick information gathering and distribution, but of also of making sure that it is distributed to the right people, in the right format and with enough completeness to support awareness and decision-making, but no so much as to increase overload. The examples of poor information quality in Table 3-10 help make the case for this multi-dimensional view of information quality.

information quality,

The findings related to information management activities show that despite the existence of ICT support and of an exclusive information manager (IM) role, there are still weaknesses in getting the right information and making sure that it complies with quality standards before being sent out to those who need it. This suggests the addition of information management services that can provide additional support for increasing information quality and as a result improve coordination. In the case of the Port of Rotterdam, introducing the use of these services would require the IM. This is because introducing new technologies into crisis response often fails due to the highly specialized practices of responders. The IM would fulfill the role of an intermediary in charge of information management activities. This mediation should initially play a prominent role, especially during training, to disseminate the new work practices and the use of the new information management services. However, explicit mediation should be phased out as the role of the information manager gradually stabilizes and the information services become widely used by other responders.

and information management.

3.5 Reflection on the Case Studies

From the point of view of design science research, the case studies are part of the *Relevance Cycle*. The goal was to provide empirical content to the conceptual framework presented in Chapter 2, as well as context-dependent findings related to the coordination issues and guidelines for crisis response information systems from Chapter 1. The first case study provided a set of observations classified according to the information processing (I-P) view providing real-world empirical observations attached to the different kinds of coordination dependencies and mechanisms. The second case study complements the first one by adding empirical content related to the initial coordination issues and guidelines by addressing the connection between coordination and information quality.

The cases add empirical content to…

The first case study found that the generic I-P categories of coordination dependencies and mechanisms can help analyze coordination issues in crisis response exercises. It also highlighted the opportunity of extending or revising the I-P view and its emphasis on standardized and mediated information exchange. Role negotiation, practice-based coordination and improvised uses of ICT can all improve either the effectiveness or efficiency of coordination when standards and hierarchy fail in crisis response. Nonetheless, different coordination mechanisms and ICT tools will be used simultaneously indicating that it is not simply a matter of fit or optimization, but of exploration of this complex surface of possibilities.

the I-P view of coordination,

the role of ICT, and its associated…

Since coordination depends on rapid exchange and comprehension of information, explicit consideration of strategies for enhancing information search, processing and exchange creates the possibility of increasing coordination (Comfort, Dunn *et al.*, 2004). Table 3-8 provides guidelines on how information quality attributes can contribute to solving coordination problems. Of the initial set of coordination issues presented in Chapter 1, it can be seen that additional information quality can help deal with heterogeneity, information management, information overload, uncertainty, adaptability, improvisation and time pressure. The findings from the second case study provide examples of the kinds of hurdles encountered that could be improved to enable this increase in coordination capabilities through the support of information quality.

guidelines.

In terms of the guidelines for ICT support in crisis response mentioned in Chapter 1 (see Table 1-1), the second case study explicitly addresses the one related to information collection, analysis and exchange, which can be mapped to the information management activities in Table 3-6. Those same activities, when carried out with high information quality can also contribute to the guideline that ICT should support open, multi-directional and integrated communication. The first case study also provided evidence that agrees with the guideline of modeling, simulation, training and routine use. Simulation was used as a tool for training, while routine use of ICT tools was echoed by interviewees. Finally, the first case also supports the guideline of having knowledge stored about lessons learned and experts available. Especially through the use of the CrisisSim and MultiTeam tools, it is expected that groups of experts can be part of specific crisis related conversations and that the logs of training exercises can be used for evaluation.

Besides crisis response exercises, simulation …

Doing research on the use of ICT to enhance information management during a crisis is not trivial, since recreating crisis scenarios is challenging; thus, the two main approaches to recreate crisis scenarios are drills and simulations (Massaguer *et al.*, 2006). However, continuously running drills is expensive and simulating a disaster entirely by software lacks realism (*ibid.*). This suggests that a combination of the two might contribute to dealing with their individual limitations. Having used crisis response drills in this chapter to add empirical content to the I-P view of coordination, the next step should then be to develop a simulation model that enables experimenting with different coordination mechanisms.

can contribute insight into coordination.

Such a simulation can contribute to testing the conditions under which a coordination mechanism can outperform another, in other to gain insight into the relative benefits of bottom-up mutually adjusted coordination versus top-down mediated coordination, which represents a critical tension in crisis response. The simulation model can thus be thought of as a tool for exploration of the complex surface of possibilities related to coordination that can provide theoretical and practical insight for understanding and planning coordination in crisis response. As such, it can contribute an artificial setting for comparing coordination mechanisms and provide arguments for designing strategies or revising preconceptions.

4 Emergent Coordination and Agent-Based Simulation

4.1 Introduction

Chapter 1 presented some of the most pressing challenges for coordination in multi-disciplinary crisis response. These included the presence of multiple response agencies and multiple organizational levels resulting in tradeoffs or conflicts between individual and team decision-making and action, as well as between the need for preparedness, planning and control, and the need for flexibility, adaptation and improvisation. The tension between local and global behaviors crucially alters the way in which coordination is achieved. This results in the recognition that to better understand and support coordination in crisis response, the role of emergent coordination needs to be addressed.

Ch. 1: the relevance of emergent coordination.

In order to present the dominant understanding of coordination in crisis response, Chapter 2 discussed the information-processing view of coordination, in which standards, mediation (hierarchy) and mutual adjustment are seen as the main kinds of coordination mechanisms. However, several alternatives and critiques were presented to show that some researchers believe the I-P view to be limited to more static or closed organizations. Those alternatives focus on heterogeneous, temporary, and sometimes non-collaborative organizations where establishing standards or hierarchies in advance might be impossible or limited. Most of these alternative views emphasize the role of emergence and emergent coordination, but no formal definition of emergent coordination or how exactly it can be related to the existing constructs of the I-P view was offered.

Ch.2: the I-P view of coor-dination and its limits.

The case studies in Chapter 3 applied the constructs from the I-P view of coordination to the analysis of crisis response practices, showing how they enable a systematic way of identifying and classifying coordination dependencies and the mechanisms used to manage them. In addition, the cases also showed that different coordination mechanisms can be used simultaneously, that ICT use can be combined and used in an improvised manner to support coordination needs, and that emergent coordination (i.e. practice-based and role-based) also occurred. However, it lacked an extended framework for characterizing and describing those coordination mechanisms as emergent.

Ch.3: applying the I-P view.

The present chapter addresses those open issues providing additional concepts and discussion of emergent coordination. From the point of view of the three-cycle approach to design science used in this research, this chapter re-enters the *Rigor Cycle* to contribute new constructs that extend or complement those from Chapter 2. By returning to the “knowledge base” it is possible to provide more rigorous definitions of emergence and emergent coordination. This leads to

This chapter: emergent coordination and agents.

a discussion of (emergent) coordination in multi-agent systems, where both emergence and coordination have been studied in the past. Agents are a suitable analytical unit of emergence and can be used to create models that both exhibit emergent properties and for which coordination is a constant concern. Agent-based simulation in particular will then be discussed as the corresponding way in which it is possible to study and compare different coordination mechanisms in the domain of crisis response. The actual use of agent-based simulation will then constitute the entry into the *Design Cycle* and the subject of Chapter 5.

4.2 A Review of Emergence

The emergence of emergence in crisis response

Emergence in crises: changing perspectives.

Emergent group behavior is often understood as aggregate behavior that differs from combined behavior in that it is not equivalent to the sum of individual behaviors. Through emergence it is possible for complex behavior to arise from simple local behaviors over time. In traditional systems design, such complex behaviors were sometimes seen "as 'parasitic' or to be avoided" given their unpredictability and potentially counterproductive outcomes, but are now increasingly being harnessed for useful purposes (Lynden, Rana, Margetts, & Jones, 2000). In crisis response, a similar trend can be seen, reflecting a shift from neglect, reject or caution, towards understanding, embracing and supporting emergence. A notable example is the recognition of emergent groups and coordination by feedback at the Disaster Research Center (DRC).

The view of the Disaster Research Center…

Aguirre, Dynes and Quarantelli at the DRC understood that no one set of standards can regulate the activity of professional crisis responders (Dynes & Aguirre, 1979). In line with the information-processing view, they argued that as diversity and uncertainty increase, coordination by feedback is more likely than coordination by plan. The consequence of their findings was that crisis response organizations which emphasize coordination by plan are following a questionable strategy by ignoring that crises create the conditions where such plans are inappropriate. However, according to them, post-disaster evaluations often use criteria dominated by coordination by plan, which creates a paradox that challenges the preparation for crisis response, torn between the need for flexibility and the demand for control and responsibility.

emphasizes emergent coordination …

Accordingly, to guide crisis management and planning, researchers at the DRC made a strong case against the dominance of the command-and-control model, favoring instead emergent resource coordination (Quarantelli, 1989). They found that command-and-control was not only a poor model for crisis response coordination, but was actually not even applied in the reality of crisis response operations. Rather than having control from above as the goal, they advocated for mutually agreed upon co-operation (Quarantelli, 1997). Nonetheless, they also recognized the fact that there would still be a simultaneous presence of emergent and structured aspects and thus suggested that the two should be blended together. Rather than assuming emergent behavior to be dysfunctional or inappropriate, they said it should be taken for granted and incorporated into the way of thinking and acting (Quarantelli, 1997).

The ubiquity of emergence during crises, was most obvious in what they called "emergent groups", which are entities with no existence before the crisis, of transitory existence but crucial to the response (Quarantelli & Dynes, 1977). The pervasiveness of emergent groups, such as welfare agencies, search-and-rescue teams, and temporary overall community-coordinating groups, forced researchers to acknowledge their presence and study their constitution, rather than consider them aberrations. A recent account of emergent groups is that of Majchrzak *et al.* (2007). They depart from the same kinds of issues presented in Chapter 1: during large-scale crises, plans break down, authority structures and communities react in unforeseen ways, communication links break down and information quality falters. As a result, emergent response groups are characterized by a great sense of urgency and high levels of interdependence under changing conditions. As such, these groups have flexible task assignments, fleeting membership and possible multiple conflicting goals, resembling swarms rather than traditional groups. These characteristics exposed the limitations of existing formal (bureaucratic) organizational theory to recognize and study emergent response groups (Majchrzak *et al.*, 2007; Quarantelli & Dynes, 1977).

and emergent response groups.

During the thirty years in between Quarantelli and Majchrzak, the popularity of complexity science and complex adaptive systems (CAS) contributed to this shift in focus, as can be seen in the more recent work of Comfort *et al.* They also recognize that under the urgent and dynamic conditions of disasters, hierarchy will almost always fail due to break down – if a node fails, large portions of the response network can become isolated – or to its inability to adapt (Comfort & Kapucu, 2006; Kapucu, 2006). In line with the DRC view, they claim that coordination shifts away from control (as in a hierarchical or planned strategy) and becomes a fundamentally voluntary activity where participants continuously learn and adjust their actions through feedback (Comfort, Dunn *et al.*, 2004). This adjustment through feedback leads (or may lead) the response organization to self-organize. Since self-organization is the driving force behind complex adaptive systems, then Comfort and others contend that the concept of CAS offers a theoretical framework that can contribute to finally bridging the gap between order and flexibility in crisis response.

Complex adaptive systems are adopted…

When used in this context, CAS can serve as a theoretical lens as well as a guide for designing support systems. In CAS, individuals are able to adapt to changes in the environment, based upon new incoming information; thus, the interacting components represent a complex system with recurring patterns of information search, exchange and adaptive behavior (Comfort, Dunn *et al.*, 2004). Crisis response itself can be viewed as a complex system with fuzzy boundaries and diverse members who come from different parts of the organization and serve one or more crisis response tasks (Paraskevas, 2006). A key principle is that self-organization occurs in response to each individual's perception of the situation, rather than through a central control mechanism. Should this self-organizing emergent organization be successful, then the crisis should also move to the resolution stage. But as pointed at earlier, there is no guarantee that the self-organization will be successful. A complexity-based approach to structuring a crisis response system should thus provide enough structure for information to

as a new theoretical lens with…

flow easily between components, yet allow enough flexibility for self-organization at the operational level (*ibid.*).

practical implications.

Another application of CAS concepts in crisis response considered the provision of emergency medical services in rural areas as part of an inter-organizational system in which relationships between independent organizations are fostered with ICT (Horan & Schooley, 2005). They applied the concepts from CAS for theoretical orientation in a case study of intelligent transportation systems finding that many organizations were greatly reliant upon technology to coordinate their actions. The use of location-specific devices (e.g. mobile phones) and wireless networks enabled the emergency medical services to keep-up with an emergent demand adaptively. A similar approach can be found in (Sapaty *et al.*, 2007) where they propose the use of a "revolutionary" programming language which can be used in most portable devices to enable them for distributed computation in an emergent manner, supporting, among others, self-organization in crisis relief missions. It is with this kind of considerations in mind that Shneiderman and Preece (2007) proposed the introduction of a US-wide community response grid to use existing Web-based social computing services for reporting, receiving information and requesting resident-to-resident assistance during an emergency.

Emergence in complex adaptive systems

Emergence…

From a systemic perspective, the moment the interrelationships between the elements of a system come into focus, new characteristics appear which are not reducible to the elements or their special characteristics, these constitute the system's emergent properties, which the separate parts do not have (Axelrod & Cohen, 2000, p. 15; Georgiou, 2007, p. 43). In complex adaptive systems, this results in apparent great complexity from simple rules (Gell-Man, 2003). Such aggregate behavior takes the form of unexpected structures, patterns, properties, or processes in a self-organizing system, which usually persist despite continual turnover in its constituents (Dooley & Corman, 2002). The difference between emergence in (complex) systems and emergence in complex "adaptive" systems is that for the latter the aggregate behavior is usually far from optimal and thus the system continues to evolve and exhibit new forms of emergent behavior (Holland, 1992). As a result, the system has little or nothing in the way of central control, having instead many distributed, interacting parts.

is open to multiple definitions, including:

Despite this general notion of emergence, there does not seem to be an undisputed definition of emergence or agreement on how to identify or measure it. Whether it is surprising or not, whether it is a phenomenon produced from the bottom-up or influenced from the top-down, or whether it implies more or less complexity at the aggregate level is a matter of ongoing discussion. According to Dessalles *et al.* (2008), this creates two dimensions for characterizing emergent phenomena: irreducibility and novelty. On the first dimension, reducible emergent phenomena can be labeled as weakly emergent and irreducible emergent phenomena as strongly emergent, following the work of Bedau (1997). On the second dimension, when there is novelty in the emergent phenomenon, it can be a result of diachronic determination, whereas a lack of novelty can be characterized as synchronic.

Nominal (reducible) emergence concerns the existence of some macro-property that cannot be a micro property, but is nonetheless a result of micro properties. This bottom-up causation result in aggregate behavior that is more than the sum of the parts, but is still predictable and expected from the intended configuration or design of the parts. This means that the micro properties will be known and their aggregate behavior will be intended. *Weak emergence* is a subset of nominal emergence for which the emergent phenomenon is not easy to explain (or trivial to infer from the properties of the parts and the law of their interactions). Thus, weakly emergent phenomena need to be simulated to be revealed (Bedau, 1997). An example of weak emergence would be shapes emerging from the simulation of cellular automata, where, for example, specific shapes emerge out of individual automata taking on a specific color at each time-step. This emergence is nominal, because the resulting shape (e.g. a bowtie) only exists at the aggregate level, whereas the local automata can only have the property of being squares; and it is weak because the aggregate shape (although composed of squares) is not trivial to infer from the local laws of the automata, thus requiring simulation to show it.

weak (nominal) emergence,

The difficulties surrounding weak emergence are that empirical observation is generally the only way to discover it and that most forms of weak emergence (given its ubiquity) are non-interesting (Bedau, 1997). Thus, observation and determination of the interest value make it a kind of emergence susceptible to bias and dependent on context. A subtype of weak emergence that attempts to deal with this "weakness" is *pattern emergence* (or "structural emergence") which restricts weak emergence to a non-random property of the system that is distinct from any property possessed by the initial state of the system (Humphreys, 2008). This non-randomness present in the novel structured pattern implies an "interesting" case of weak emergence, and the fact that it does not exist at the initial state also makes it a kind of diachronic emergence, which will be presented in brief.

pattern emergence,

Strong (irreducible or holistic) emergence, the opposite of nominal, states that emergent properties have irreducible causal power on the underlying entities: macro causal powers effect on both macro and micro levels (downward causation). The difference with weak emergence is that the aggregate behavior and structure effects a top-down feedback on the micro-level. Indeed, the "pivotal feature of this definition is the strong form of downward causation involved" (Bedau, 1997). Some argue that strong emergence should be left as a conceptual perspective on emergence, for which it is very hard to find real world examples and for which the notion of *irreducible downward causation* creates an unnecessary "mystery" with little or no scientific relevance (Bedau, 1997). Moreover, strong emergence usually also implies some form of weak emergence, making the separation artificial. According to Dessalles *et al.* (2008), first weak emergence appears producing a collective structure observed by the local agents. Through inter-agent communication, these observations produce collective ideas or concepts, which are then used by agents for their subsequent behavior, resulting in strong emergence. This would also make strong emergence diachronic in nature (as will be seen below). For example, a simulation of a flock of birds emerges out of simple local rules of movement, but once the flock emerges it restricts further movement at the local level. Using the crisis response organization as example, once it has emerged from heterogeneous agents, it creates global conditions of interaction which influence the way in which individuals act and communicate

strong emergence,

with each other, as in the volunteer organizations that emerged after the WTC attacks in 2001, which ended up creating certain rules of interaction and semi-standard tasks that developed in an *ad hoc* manner but were later adopted by newcomers (Voorhees, 2008).

On the novelty dimension, Dessalles *et al.* (2008) place *synchronic emergence*, which postulates that a macroscopic emergent phenomenon can be explained by the current (synchronic) interactions of the interrelated microscopic entities. This implies a coexistence of higher level properties with properties existing at some lower level (Humphreys, 2008). This kind of emergence, though conceptually valid in a general sense, is challenged by those who claim that historicity is ineliminable when considering emergence. The underlying premise is that "the historical development of a system's dynamics is often crucial to the system's terminal state's being emergent" (*ibid.*). On the other side of the spectrum we find *diachronic emergence* which postulates that emergent phenomena develop across time by means of sequential adaptation of microscopic entities (Dessalles *et al.*, 2008). For example, synchronic emergence during a crisis can be seen in the multi-disciplinary crisis response organization as composed of agents from the different response disciplines, none of which are capable in themselves of responding to the crisis. Although the organization itself changes over time, its identity as a crisis response organization lasts from its first inception to its final dissolution as a synchronic property. A diachronic emergent property of that same organization would be one which shows that, after a while, the communication network between the agents exhibits the property of a small-world network (Comfort, Ko *et al.*, 2004). Determining the characteristics of the communication network as being "small-world" or "scale-free" – *cf.* (Huberman & Adamic, 2004) – requires analyzing their communication patterns as they emerge over time.

and synchronic or diachronic emergence.

4.3 Coordination in Multi-Agent Systems

Emergence can be simulated with…

Regardless of the definition or categories, the previous notions of emergence are built with the understanding that agents can be used to model the individual components of the system, for which the local behaviors and interaction rules can be defined in advance in order to simulate emergent properties at the system level. This makes agents an ideal building block for multi-agent systems (MAS) that produce emergent phenomena.

agents organized in a…

In the artificial intelligence field, intelligent software agents were conceived to help deal with the increasingly difficult task of searching, collecting, filtering and evaluating information from multiple sources. The resulting notion of agents as personal assistants had them as "programs that act on behalf of their human users to perform laborious information-gathering tasks" (Sycara, Pannu, Williamson, Zeng, & Decker, 1996). Since the agents themselves were not exempted from the constraints of bounded rationality, distributed artificial intelligence was necessary for building multi-agent systems that could "compartmentalize specialized task knowledge and organize themselves to avoid bottlenecks" (*ibid.*). This resulted in providing not just intelligence at the agent level, but also mechanisms for communicating and interacting with other agents and humans.

MAS are justified for simulating emergent phenomena, as opposed to for example genetic algorithms or cellular automata, because of their ability to integrate autonomous, decisional and heterogeneous agents (Habib, 2008). A multi-agent system can be "conceived as an *organized society* of individuals in which each agent plays specific *roles* and interacts with other agents according to protocols determined by the roles of the involved agents" (Zambonelli, Jennings, & Wooldridge, 2003). The key concepts of a MAS are of course the agents themselves, but also the communication needed to achieve a global behavior from the interaction among constituting agents (*ibid.*). Such characteristics enable multi-agent systems for simulating emergent behavior, but also different mechanisms for coordinating the interactions among the agents.

multi-agent system,

It is no wonder then that the interdisciplinary study of coordination contributed by Malone and Crowston (1994) was conceived in part as a result of their work with multi-agent systems. A definition of coordination for MAS specifically adapted from Malone and Crowston is "the support for the activity of managing dependencies and possible conflicts between agents involved in common and inter-related tasks of a collaborative activity" (Coates, 2006).

also ideal for studying coordination.

Emergent coordination in MAS

Usually emergent coordination in MAS, from a CAS perspective, is linked to achieving self-organization inspired in social biology (e.g. ant-foraging techniques and swarm intelligence) (Jiang & Liu, 2006). In this sense, emergent coordination forms a class of models and frameworks in which the coordination does not occur as the central part of the interaction; there is no direct correspondence between the purpose of local interaction, and the global functionality of coordination at the system level (Ossowski & Menezes, 2006). A corresponding notion of emergent coordination for MAS then refers to the outcome of interaction of autonomous agents driven by self-interest and not aware of the global (and hopefully coordinated) outcome of their aggregate interactions (*ibid.*).

Emergent coordination in MAS can be…

Since micro-level mechanisms allow designing single agents but designers are mostly interested in macro-level system design, bottom-up solutions are mandatory (*ibid.*). Nonetheless, multi-agent systems attempt to combine the advantages of both dependent (centralized, top-down) and emergent coordination. Dependent coordination is useful to provide control, while emergent coordination can be used to improve how the coordination mechanisms themselves are implemented efficiently (*ibid.*). This creates an opportunity for evaluating and comparing bottom-up and top-down coordination mechanisms.

compared to other (top-down) mechanisms…

One possibility is to classify and compare the relative advantages and disadvantages of different coordination mechanisms based on their theoretical characteristics. For example, Frozza and Alvares (2002) provide a comparison of a set of generic MAS coordination mechanisms, in terms of predictivity, adaptability, action control, communication mode, conflict resolution, information exchange, type of agents supported, and application domain. Scerri *et al.* compare three approaches to large-scale coordination, based on their common algorithms and principles, their key novel ideas, their underlying software and any open problems left in each approach (Scerri, Vincent, & Mailler, 2006). Using the paradigm of design patterns, de Wolf and Holvoet (2007) create a problem-based

based on their characteristics or…

catalogue of decentralized coordination mechanisms (digital pheromones, gradient fields, market-based, tags and tokens) that could be used for specific kinds of problems (at design time) to achieve emergent self-organization in MAS.

through simulation.

An alternative to comparing the general characteristics, advantages or disadvantages of different coordination mechanisms is to implement and simulate them. This enables comparing and measuring the effectiveness, efficiency or utility of different coordination mechanisms before deploying them in real-life systems, as well as increasing the insight about those mechanisms to improve their design or combination with other mechanisms.

Agent-based simulation of coordination

Agent-based simulations of emergent phenomena…

One of the main reasons for agent-based modeling and simulation is to capture emergent phenomena (Bonabeau, 2002) or highlight the phenomenon of emergence (Dooley, 2002) and especially of social emergent structures existing in the real-world (Epstein & Axtell, 1996). Agent-based simulations can mimic emergent phenomena such as: standing ovations, human and animal migrations, and traffic jams, among others.

include: emergence of coordination,

Through agent-based simulation, it has also been possible to show the emergence of coordination in different settings, particularly using the concepts and social dilemmas from game theory. In one case, heterogeneous agents (with different preferences) are simulated in a “minority game” to show under what conditions the interaction of beliefs and behavior at the micro-level is likely to produce efficient patterns of interaction at the aggregate level (Bottazzi, Devetag, & Dosi, 2002). Their simulations show that in minority games, where it pays off to be in the minority, efficient coordination does not stem primarily from adherence of populations of agents to Nash equilibrium, but rather out of persistent “ecologies” of heterogeneous beliefs and behaviors.

and emergent properties of coordination,

In another use of agent-based simulation, the starting point is that emergence cannot be designed so they use tuple-spaces and stochasticity to enable an exploratory simulation of coordination models that can show their emergent (understood as unexpected and possibly undesirable) properties before implementation (Casadei, Gardelli, & Viroli, 2007). Their goal, however, is not to simulate the emergence of coordination, but rather the emergent properties of particular coordination models.

with or…

In another example, a simulation of the Stag-Hunt game is used to explore different configurations to achieve maximum coordination. Their results show that the ability to communicate (specifically in pre-play about strategic preferences) enables improved coordination (J. H. Miller & Moser, 2004). They also show that without this communication (or without the ability to process communication) the coordination points selected will be less optimal than those using communication.

without communication.

Alternatively, in a distributed problem-solving case, Sen *et al.* (1998) simulate agents independently assigned to move a block. Using reinforcement learning (where agents get a payoff from moving the block as a difference between the reward of moving it and the effort of getting there) they show that although each agent is independently optimizing her rewards, global coordination can (though not always) emerge without explicitly or implicitly sharing information.

Within MAS research, simulation is often used to compare alternative coordination mechanisms. Often, distribution of tasks based on costs and rewards is used to compare the performance of different coordination mechanisms (Excelente-Toledo & Jennings, 2003). In one example, congestion games (such as selfish task allocation or selfish routing) are used to measure different coordination mechanisms in terms of "the price of anarchy", where the best coordination mechanism is the one that results in minimal price of anarchy resulting in the premise that without any coordination mechanism, such price is unbounded (Christodoulou, Koutsoupias, & Nanavati, 2004).

They can also be used to compare or…

More context-dependent approaches are aimed at evaluating (rather than comparing) coordination mechanisms in specific domains. In one example, they use coordination mechanisms for production/marketing choices, showing through simulation that it performs better than using a single coordinating agent or no coordination mechanism at all (Kwon & Lee, 2002). An important difference in this example is that it measures not just the cost of coordination, but also domain-dependent factors (profit, inventory level and ROI).

evaluate coordination mechanisms …

Similar approaches have been used in the domain of crisis response. In one case, a particular coordination mechanisms is used in the simulation of fire trucks, showing that the coordinated actions are more robust (scalable) and flexible than without such mechanism (Xu, Liao *et al.*, 2006). In another example, a set of coordination mechanisms are used in the simulation of emergency medical services in terms of coordination efficiency and also using the domain-dependent metric of response time (Chen & Decker, 2005).

in crisis response.

Besides their expressive power in terms of emergence and coordination, agent-based modeling is adequate for conceptualizing a crisis response organization. When a crisis or emergency occurs it gives rise to an incident organization, which is a temporary organization of otherwise disparate resources drawn from many agencies (Smith & Dowell, 2000). Within this incident organization lies a disaster management system comprising the people, technology and procedures concerned with directing resources (Smith & Dowell, 2000). Participants in this disaster management system may not have worked together before. Moreover, large-scale emergencies are often beyond the capabilities of the permanent staff and facilities available (Liu, 2004). The resulting *ad hoc* crisis response teams must be formed quickly, assigned roles and responsibilities, and deployed. The teams are not fixed, but evolve as the availability of personnel, including volunteers, fluctuates. The corresponding entrance and exit of teams increases the difficulty of coordinating the response. As response operations evolve, interactions also need to be redefined for each succeeding situation (Comfort, Ko *et al.*, 2004).

Agent-based modeling is suitable for...

Since the military command and control system is effective in deploying resources, some believe it must be capable of effectively providing rescue and relief services, but the military is not trained or structured for the complex tasks of intergovernmental coordination and collaboration needed when preparing for and responding to extreme events (Harrald, 2006). In addition, while hierarchical networks work efficiently during routine operations, they do so poorly in the

conceptualizing a crisis response…

dynamic environment of crises, where node failure may isolate large networks from each other (Kapucu, 2006). This has resulted in the tendency towards designing emergent and dynamic networks, rather than formal, static and hierarchical organizations (Houghton *et al.*, 2006; Weigand, 2006). In practice, most crisis response organizations already exhibit some degree of autonomy, while preserving some centralization (Harrald, 2006; Houghton *et al.*, 2006).

organization.

In brief, *ad hoc* crisis response organizations are multidisciplinary and fluctuate in size. Additionally, they exhibit hierarchy and centralization together with emergence, autonomy, openness and scalability. If we define an organization as an open system consisting of cognitively restricted, socially situated, and task-oriented actors who interact with other members of the organization and are affected by ambiguity and past experience, then computational models can be used to encapsulate this view and generate predictions regarding the design of an organization for effective performance in response to a crisis (Lin, Zhao, Ismail, & Carley, 2006). An adequate computational model, given the characteristics of crisis response organizations is a multi-agent system (MAS). Such a system may exhibit similar characteristics, such as a distributed organizational framework, mobility and self-coordination (Dooley & Corman, 2002; Weigand, 2006).

4.4 Discussion

Crisis response exhibits emergence of…

Chapter 1 presented some of the most pressing challenges for coordination in multi-disciplinary crisis response. The presence of multiple response agencies and multiple organizational levels tends to result in tradeoffs or conflicts between individual and team decision-making and action. There is also a widely acknowledged tension between the need for preparedness, planning and control, and the need for flexibility, adaptation and improvisation. But such tradeoffs do not necessarily imply mutually exclusive goals or behaviors; rather, they indicate the presence of emergent properties and behavior, which are constitutive of the local entities (the responders) as well as of the system as a whole (the multidisciplinary crisis response organization).

coordination and of…

Emergence of coordination from the bottom-up does not need to oppose coordination established from the top-down through plans or hierarchy. In Chapter 1 there are two examples in which coordination emerged from the bottom-up, resulting in organized, hierarchical, and even semi-standard crisis response procedures, which became the *de facto* coordination mechanisms thereafter (valid throughout the crisis, but not beyond). However, whether effective and efficient coordination mechanisms do emerge, and whether they do so in time cannot be expected every time.

ICT use.

Since emergent behavior does occur, the expectation that ICT should be used to support planned coordination mechanisms may be limited. Chapter 2 mentioned the work of Orlikowski and colleagues who developed the notion of "technology in practice" to assert that the use of technology is contingent, contextualized and situated. In this view, technology changes through human action, particularly through emergence and improvisation. In terms of coordination, the same is to be expected: "situated coordination" results in the emergence of organization out of ongoing interactions between individuals and technology. The ensuing emergent coordination is not a product of bottom-up interactions alone but also of the reshaping of those interactions within the resulting global structures.

From the notions of emergence in complex adaptive agent-based systems discussed in this chapter, it is possible to extract a general definition: *emergence is a central property of complex dynamic systems based upon interacting agents which results from confronting the agents within a specific structure of interaction, neither at the level of the whole nor at the level of the agents, but constitutive of both.* This definition specifically draws upon the premise that the properties of the whole system result from the collective interactions between the agents by upward (bottom-up) causation; but, to some extent, agents may also be constrained by the whole top-down process (Dessalles *et al.*, 2008, p. 256).

A definition of emergence, applied to coordination,

When applied to coordination, this definition of emergence in multi-agent systems means that emergent coordination can be achieved from the bottom-up through agent goals or rules that are described independently from the coordinated global goal – e.g. local beliefs and behaviors may result in aggregate patterns of interaction. In terms of the types of emergence presented earlier, this would make emergent coordination a case of nominal and more specifically weak emergence. In addition, when decision-making and action become coordinated this can be characterized as patterned or structured emergence, as opposed to emergence of random aggregate phenomena.

suggests that it is weakly, patterned, but also…

However, coordination mechanisms are often used in combination and may be selected in design or run-time, including both bottom-up and top-down mechanisms. Moreover, once coordination has emerged it may have a downward effect which influences further interactions between the agents. This suggests that often coordination moves from weak to strong emergence. Also, given the fact that a multi-agent system aims at gradually solving a problem by achieving coordinated action, emergent coordination is also a case of diachronic emergence.

strongly and diachronical-ly emergent, leading to…

This chapter departs from the simplified I-P view that coordination moves from standards to mediation to mutual adjustment. Emergent coordination in crisis response, informed by complex agent-based adaptive systems, places more emphasis on mutual adjustment and on the combined use of mechanisms for a multi-disciplinary organization that cannot rely only on pre-defined plans and command and control. In revised I-P terms, information processes drive the dynamics of organizational adaptation and self-organization as each response agency reciprocally adjusts their actions to changing conditions; it is this emergent self-organizing behavior which leads to the mutual adjustment that represents coordination in practice (Comfort, Dunn *et al.*, 2004). Furthermore, from a purely nominal point of view, we could ask whether there actually needs to be a distinction between emergent and non-emergent coordination in multi-disciplinary crisis response. Given that coordination centers on interactions between the disciplines to manage dependencies between the activities that must be achieved jointly, coordination is an emergent property of the system, not of the individual agents. The question – posed from an I-P view of coordination – shifts towards the issue of whether coordination is imposed by hierarchical mechanisms, if it is enabled by standards or if it is a result of mutual adjustment.

a departure from the I-P view of coordination.

Focus is now simulating coordination mechanisms,

A general answer that can be drawn from this chapter is that coordination during a crisis will emerge as a combination of the three kinds of coordination mechanisms, involving situated and simultaneous uses of them whether supported with ICT or not. The focus then turns to evaluating and comparing such coordination mechanisms in specific crisis conditions, ideally through the use of agent-based simulation. This should enable an improved understanding of coordination in crisis response as well as being the basis for designing ICT-support for those mechanisms. The ability to create a simulation model to compare and experiment with coordination mechanisms *in silico* is made possible within the framework of the I-P view and agent-based modeling.

using theory from the I-P view and this chapter.

The present chapter has contributed the constructs (agents, emergence, and emergent coordination) and methods (agent-based simulation) to be used in the development of the simulation model. In addition, these constructs and methods help extend and add insight to the constructs of the information-processing (I-P) view of coordination. *Dependencies* are part of the understanding of coordination in the context of agents. Indeed, many discussions of coordination in multi-agent systems are guided by Malone and Crowston's definition. The use of *coordination mechanisms* is equally prevalent throughout the literature in MAS coordination with or without simulation, where the mechanisms are implemented as algorithms, organizational structures or protocols. Such mechanisms are amenable to be classified, following the information-processing view, as based on standards (plans), mediation (hierarchy), or mutual adjustment (feedback).

The relevance and rigor cycles suggest …

The contributions from the relevance and rigor cycles suggest specific design considerations. Standards and mediation can be included in a simulation model in the form of a hierarchical topology, which is based on current crisis response organizations (the Dutch case in this research). Since this chapter suggests agent-based modeling as an appropriate way of representing the crisis response organization, additional standards can be implemented through pre-defined interaction protocols that the agents use to communicate.

specific considerations for the …

Mediation can be operationalized with a shared data space (SDS) that the agents from different disciplines can use. This SDS can illustrate the potential value of ICT support, particularly in improving information quality as presented in Chapter 3 (e.g. accuracy, completeness, format divergence and consistency). Alternatively, the same dependency can be managed with mutual adjustment of local autonomous decisions. This should contribute a meaningful example for comparing coordination mechanisms in crisis response. A similar comparison can also be provided without specifically focusing on ICT support and to provide insight into intra-disciplinary coordination as well. To explore this option, one of the response disciplines can use two coordination mechanisms for assigning specific tasks to individual response agents: either through the mediation of an operational leader or through the autonomous decisions of individual agents.

design cycle: developing a simulation model.

By running experiments with the simulation model, it should be possible to analyze the results and detect patterned or structured data in the form of non-random global behaviors. By operationalizing the coordination alternatives as binary factors, it should also be possible to test their effect on achieving the structured outcome and, more importantly, to compare their relative efficiency and effectiveness with respect to the alternative coordination mechanism.

5 Simulating Coordination in Crisis Response

5.1 Introduction

Given the difficulties in gathering data, designing controlled experiments and getting access to real emergencies, we often have to rely on recreation of crisis scenarios for training, planning and research. The two main approaches to recreate crisis scenarios are simulations and drills (Massaguer *et al.*, 2006). In Chapter 3, two case studies of crisis response drills (exercises) were presented as part of the *Relevance Cycle* of this research. The cases showed coordination issues in practice using the information-processing view of coordination (seen in Chapter 2 and part of the *Rigor Cycle*) as an analytical framework. They also presented context-specific uses of ICT for supporting crisis response, emphasizing the link between providing information management services and improving coordination. After that, Chapter 4 went back into the *Rigor Cycle* to provide additional constructs to extend the information-processing view of coordination with emergence and agents. This previous chapter argued that to study emergent coordination and compare different coordination mechanisms in crisis response, using agent-based simulation should be useful. This chapter enters the *Design Cycle* of this research to present the development of a simulation model which enables comparing different coordination mechanisms using an agent-based model of a crisis response organization while at the same time allowing for theoretical development around coordination in crisis response in two ways: first, the conceptual model operationalizes constructs obtained in the *Rigor Cycle*, both from an information-processing and an agent-based perspective; second, it provides a testbed for experimenting with different coordination configurations in order to explore different theoretical assumptions and test the potential benefits of using specific information management support through ICT (i.e. a shared data space for mediated coordination that can also improve information quality).

This chapter enters the Design Cycle….

Simulation provides a unique way of understanding complex social phenomena and crisis response organizations in particular (Kleiboer, 1997). It is useful when the cost of collecting data is prohibitively expensive or when there are a large number of conditions to test, as is often the case in crisis response. For instance, in situations where large numbers of responders are involved, it is unfeasible to carry out experiments in real-life situations; therefore, simulations offer a valuable platform for testing strategies in advance (Suárez *et al.*, 2005). Simulation can also be used to provide a more economical method of testing contingency plans and practicing coordination between different agencies during crisis response operations, while offering a large degree of control for analysts and researchers (Kleiboer, 1997). In addition, simulation can illustrate the patterns and

with the creation of a simulation model….

pathologies of crisis decision making; they can create a great opportunity for getting acquainted with all aspects of crisis management; and they can help bridge the gap between theory and practice (Boin *et al.*, 2004).

using agents….

Agent-based simulation in particular is appropriate for crisis response, given its capacity to produce aggregate behavior (complex patterns of interactions) which emerge for the analyst or researcher to observe (Comfort, Ko *et al.*, 2004). Using multi-agent systems (MAS) for simulation can be useful in part because of the ability to quickly start with rough models and refine iteratively (Robinson & Brown, 2005). Such extensibility allows for addition of new behaviors (Comfort, Ko *et al.*, 2004) and new roles which can be integrated to and compared with old ones (Massaguer *et al.*, 2006). Chapter 4 gives a more detailed account on the benefits of using agents for studying emergent behavior and simulating different coordination mechanisms. However, in crisis response, agent-based models typically focus on response agents or organizations, but are not necessarily appropriate for modeling the crisis scenario itself. Other types of models may be required for representing the objects, events and dynamics of the environment.

and discrete-event simulation.

An often used approach to simulation is discrete-event simulation (DES). DES uses activities, events, or processes arranged discretely, resulting in a dynamic model where the passage of time plays a crucial role (Banks, 1998). As such, time-dependent events can be used for modeling the crisis-related events which the agents have to respond to. Besides events, DES models also integrate resources and entities that can be used to represent the objects, resources and infrastructure elements that the response agents must interact with and use. This chapter presents the development of a simulation model that benefits from both approaches in an architecture that combines a MAS and a DES model, integrating them but maintaining enough separation so as to preserve the qualities of each approach and enabling independent changes in both the crisis situation model (DES-based) and the response organization (MAS-based). Previous research has already tested the plausibility of combining DES and agent-based simulation (see Section 5.4), although to our knowledge not in the domain of crisis response. In addition, such efforts are mostly aimed at supporting the features of one the approaches inside the other or vice versa, while in this case each approach and tools are kept separate inside a combined architecture.

5.2 Simulation Method

The simulation method is aimed at…

The method employed for the simulation study enables developing a simulation model with the dual purpose of theory development as well as design instantiation. This is a way to address the rigor and relevance imperatives of design science research. The simulation model, as a tool for theory development, addresses rigor by operationalizing the constructs from the knowledge base and allowing for different theoretical assumptions to be simulated and new insights to be developed. As an instantiated design artifact, the simulation model addresses the relevance by providing an experimental setting for (a) comparing the benefits of coordination mechanisms with respect to each other and (b) evaluating specific mechanisms to assess potential ICT support for coordination in crisis response.

Using simulation for theory discovery or development departs from the understanding that a simulation model is the codification of a set of theoretical propositions equivalent to, for example, operationalizing constructs into survey items (Dooley, 2002). According to Davis *et al.* (2007), simulation as a research method can provide superior insight into complex theoretical relationships among constructs, especially when challenging empirical data limitations exist (which is the case in crisis response research) and can provide a powerful method for sharply specifying and extending extant theory (namely, the information-processing view of coordination in crisis response). As a design artifact, simulation can be used to aide in the evaluation of alternatives for change, giving shape to a specific design-oriented, problem-solving approach (Sol, 1982). As in Davis *et al.* (2007), the method begins with a research question and ends with a development or extension of extant theory. And as in Sol (1982), the method separates the development of the abstract (implementation-independent and data-void) model from the development of the computer simulation model to explore alternatives. Given the iterative nature of the design cycle, the simulation method itself should be considered as a cyclical way of effecting the design of the simulation model. The method activities are presented in Figure 5-1.

theory development and design instantiation.

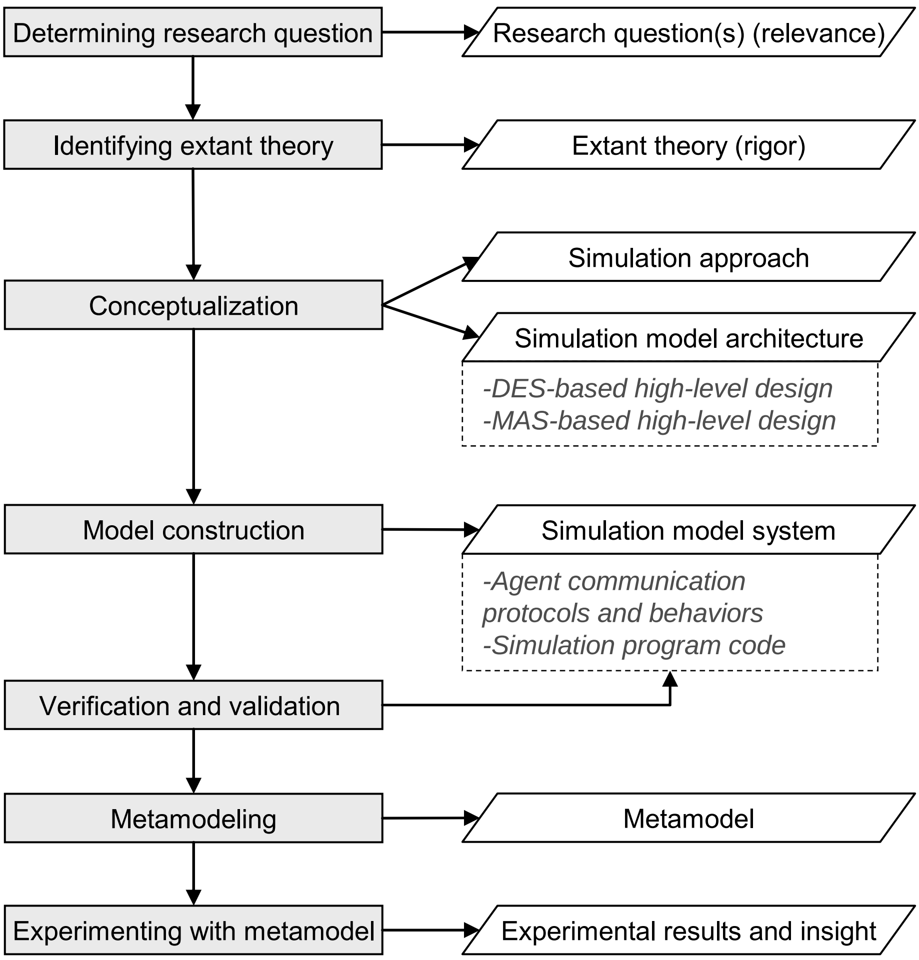


Figure 5-1 Simulation method employed in this research

Activities are: determine research question (Ch. 1);

Determine a research question. The method starts by delineating a research question of interest. On one hand, the question is motivated by a study of literature in which an intriguing tension is sought (Davis *et al.*, 2007). On the other hand, the question is explored out of observation of a real problem situation (Sol, 1982, p. 43). The research questions guiding this research were presented in Chapter 1 as a result of the literature study on coordination issues in crisis response. These are:

RQ1. How can the current understanding of coordination in crisis response be extended to account for emergent coordination?

RQ2. How does coordination based on centralized command and control compare to decentralized or emergent coordination in crisis response?

RQ3. How does an extended understanding of coordination in crisis response and of its alternative configurations contribute to bridging the gap between the possibilities and realities of ICT support during a crisis?

RQ1 explicitly addresses a theory development question, where the current understanding of coordination is the information-processing view. RQ2 embodies the main intriguing tension motivating the research. RQ3 reflects the practical implications of RQ1 and RQ2. The case studies in Chapter 3 allowed an exploration of the questions in crisis response exercises, to add empirical content through observation of a real problem situation. The simulation study now enables answering RQ2 in an experimental setting for a specific crisis scenario. In addition, building the simulation model with constructs from current understanding of coordination and using it to test different theoretical premises that can extend this understanding contributes to answering RQ1. In addition, the simulation can serve as a testbed for evaluating different coordination mechanisms that could be supported with ICT contributing to answering RQ3.

identify extant theory (Ch.2 and 4);

Identify extant theory. Because the research question is informed by studying the existing knowledge base, the second activity in the method consists of selecting the most appropriate extant theory – or *simple theory*, according to Davis *et al.* (2007) – within that knowledge base that is suitable and relevant for development. Such theory needs to shed light on the research question, highlighting the identified tension and complexities of the domain of application. It should also present challenges that are limited by the availability of data, making the inquiry suitable for a simulation treatment. The selected extant theory is an un(der)developed theory with only a few constructs and related propositions with modest empirical or analytical grounding, such that the propositions are likely correct but conceptually weak (Davis *et al.*, 2007). Revising, developing or extending this theory is the outcome of the whole simulation method.

In the present simulation study, the theoretical framework is the information-processing view of coordination (Chapter 2), revised and extended with additional constructs from emergent coordination (Chapter 4). Although the information-processing view of coordination is made up of solid concepts that have been used widely in organizational design and guide most of the discussion around coordination in crisis response, some of its organizational design premises are not applicable in the crisis response domain (see Chapter 2). As a result, the "current understanding of coordination" from RQ1 is the information-processing view of coordination (Chapter 2) and its extension with emergent coordination and agent-based modeling is expressed in Chapter 4.

Conceptualization. This activity begins by determining the context for conceptualization that most adequately fit the research question and the extant theory. The choice of context for conceptualization determines the language for conceptual modeling (Sol, 1982, p. 43). Accordingly, a simulation approach that fits this context should also be chosen, between for instance discrete-event, system dynamics and agent-based simulation (Dooley, 2002). Depending on the selected simulation approach, the conceptual model is built, resulting in an implementation-independent simulation model architecture.

conceptualization (Section 5.3);

Chapter 4 already identified agent-based modeling as an adequate representation that provides the context for conceptualization. The next section in this chapter describes the process and outcome of the conceptualization activity using this particular language, resulting in an architecture that combines an agent-based model for the crisis response organization and a discrete-event model for representing a specific crisis scenario.

Model construction. Using the simulation model architecture as the high-level design, a computer-based simulation model can then be built. This activity should transform the architecture to an implementation-dependent model expressed in computer-readable language. This is the final step in operationalizing the theoretical constructs, which remained abstract in the architecture model.

model construction (Section 5.4);

The construction corresponds to the actual instantiation of the conceptual model as an implementation-dependent simulation model which uses an agent-based platform for containing the agents, while at the same time using a specific simulation engine to handle the events, manage the animation of the scenario objects, handle the pseudo-random number generation, and organize the experimental inputs (parameters) and outputs (logs). This implies adopting an implementation-dependent method for transforming abstract agent models into implementation dependent agents. Model construction is presented in Section 5.4.

Verification and Validation. This activity is about checking the internal validity of the theory and the correctness of the model. Simulation model verification is substantiating that the model is transformed from one form to another as intended, with sufficient accuracy (Balci, 1994). The result is a verified simulation model, which implies iterating between this activity and the previous one, until the model is sufficiently verified for experimental purposes. The validation of the simulation model is aimed at substantiating that it behaves with satisfactory accuracy within its application domain and consistent with the study objectives (Balci, 1994). In a sense, validating the simulation model is a recognition that it is like a miniature scientific theory and as such subject to the problem of induction – inferring from real world observations that the model captures essential structures and parameters of the real system (Kleindorfer, O'Neill, & Ganeshan, 1998). This difficulty is especially relevant because the simulation is used for "what if" analysis and validation cannot simply be about comparing computed behavior to "real" behavior, since there is no "real" system. Accordingly, face expert validation and sensitivity analysis often takes the place of quantitative or statistical validation techniques (Dooley, 2002; Louie & Carley, 2008). Validation results, however,

verification and validation (Section 6.2);

should not be taken as falsification (Lakatos, 1978), but rather as a source for subsequent versions of the simulation model.

meta-modeling (Section 6.3); and

Metamodeling. By using Design of Experiments (DoE), the experimental results can be analyzed to estimate the importance of the individual factors. In addition, DoE can also be used as basis for obtaining a regression metamodel (Kleijnen, 1999b). This metamodel acts as a simplification of the simulation model, enabling a quicker process of obtaining quantitative and sharp insight, which would require more runs and more complex experimental designs if pursued with the simulation model directly. Thus, the verified and validated simulation model embodies the constructs, models and methods that constitute the kernel theory and design knowledge obtained in the *rigor cycle*, while the metamodel becomes the tool for revising and extending the kernel theory inside the *design cycle*. Given the cyclical nature of this cycle and the interpretive flavor of the research approach, the metamodeling effort has the dual value of providing measures for validating whether the simulation model produces the expected behavior, as well as uncovering patterns that constitute novel insights for refining the design as well as making theoretical contributions back to the knowledge base. Since the primary value of the metamodel is to make it easy to answer "what if" questions (Banks, Carson, & Nelson, 1999, p. 514), it becomes the input for the next activity.

experiment-ting to gain insight (Section 6.4).

Experimenting with the metamodel. This activity takes place in order to produce results that test the relationship among theoretical constructs, emphasizing the tensions addressed in the research question. This enables an exploration of the premises from the I-P view that might not hold in a crisis situation and of the alternative premises from emergent coordination that can enable an extended understanding. Explicitly, the premise from the I-P view which holds that coordination moves from standards to mediation to mutual adjustment as uncertainty increases, needs to be revised against the (permanent) uncertainty present in a multi-disciplinary crisis response where there is simultaneous and mutually influencing use of coordination mechanisms from all three types along with the diminished ability to design and impose any particular one in advance.

Method for developing the multi-agent system

Conceptualization is supported by Gaia.

The guiding approach for conceptualization will be agent-based modeling, as per the discussion in the previous chapter. This translates into an analysis and design for the multi-agent system (MAS) in an implementation-independent manner. The method selected for this conceptual modeling is the widely used GAIA methodology (Zambonelli *et al.*, 2003), which views a MAS as an organized society of individuals in which each agent plays one or more roles and has one or more responsibilities. Each agent interacts with other agents according to a set of protocols and these interactions are seen as the way the agent accomplishes her role in the system. In addition, GAIA is based on the bounded rationality paradigm (*ibid.*) providing fit with the information-processing view of coordination as well (see Chapter 2). Moreover, the understanding of a MAS organization in GAIA separates the agents from their environment, making the latter amenable to a different modeling approach (i.e. discrete-event based) as shown later in the conceptualization. A graphical depiction of the models that should result from following the GAIA methodology is shown in Figure 5-2.

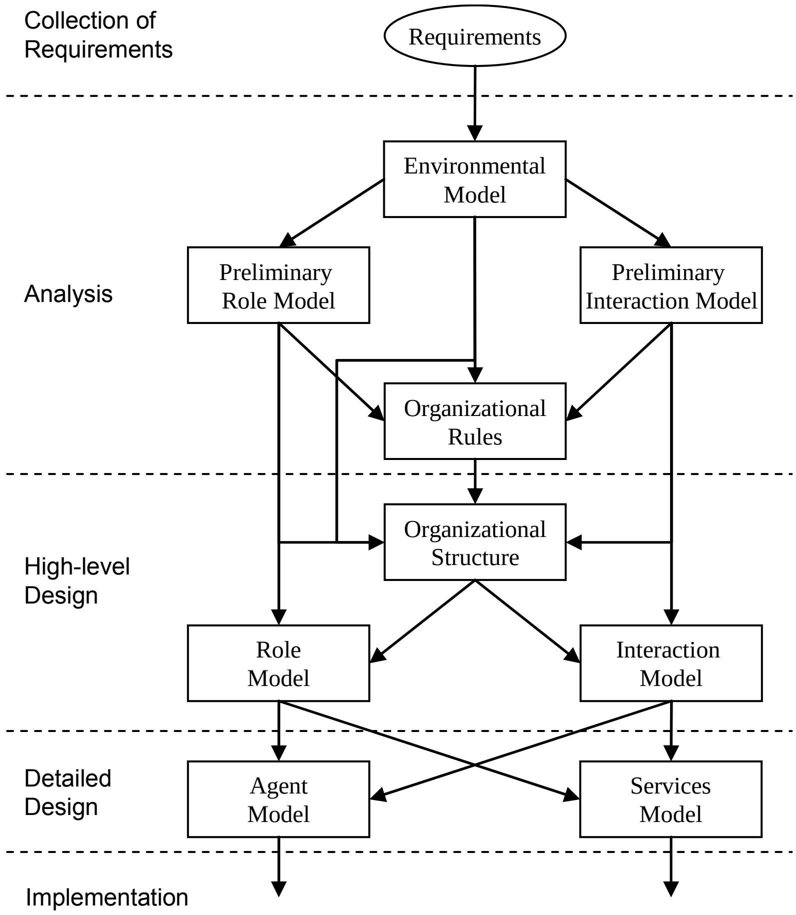


Figure 5-2 GAIA methodology, adapted from (Zambonelli *et al*., 2003)

As can be seen, GAIA is concerned with the analysis and design of the MAS organization. The agent roles, interactions and the overall organizational structure should be the result of this process. From the initial analysis of agent roles, interactions and organizational rules, GAIA moves on to the high-level design that establishes the structural properties of the system and provides more specific and formal characterizations of the roles and interactions between the agents. The final, detailed design creates individual representations of the agents, in terms of the model of each agent, and the model of the services provided by each agent.

Model construction is based on Gaia2Jade.

Since the GAIA methodology is implementation-independent, a transition is expected between the GAIA-based analysis and design of the MAS and an implementation-dependent design. The choice of JADE (Bellifemine, Caire, Trucco, & Rimassa, 2008) as the Java-based agent development framework is due to its widespread adoption, available documentation, open source character and compliance with the FIPA (Foundation for Intelligent Physical Agents) specifications (IEEE Foundation for Intelligent Physical Agents, 2009). Also, JADE has already been used for developing MAS in the field of crisis response (Bloodsworth & Greenwood, 2005; Massaguer *et al*., 2006).

The GAIA2JADE process (Moraïtis, Petraki, & Spanoudakis, 2003; Moraïtis & Spanoudakis, 2006) can be used to transform and continue the GAIA method into a JADE-dependent modeling and implementation of the MAS. According to this process, there are some steps to make the transition from a GAIA analysis and design into a JADE-based development. Because JADE is FIPA-compliant, the first step, as shown in Table 5-1, is to define the communication protocols in terms of a domain ontology and the ACL (Agent Communication Language) messages to be exchanged between the agents using that ontology. The next step defines the activities refinement together with a class diagram representation of the ontology, through which the pseudocode of the behavior of the agents and their access to environmental objects is determined. Having this, the next step is to define such behavior in terms of JADE behaviors, which implement the tasks or intentions of the agent. Finally, the behaviors are coded in Java.

Table 5-1 GAIA2JADE process, based on (Moraïtis & Spanoudakis, 2006)

Step	Input	Output	Comments
Define communication protocols	GAIA Interactions Model	Domain Ontology; ACL Messages	Messages should comply with FIPA ACL message structure. Sequence diagrams may contribute.
Define activities refinement table	GAIA Environmental, Interactions, and Roles Models; Jade Domain Ontology	Application Data Class Diagram; Activities Refinement Table	Domain ontology classes are represented as Java classes. Algorithms are documented for each liveness property.
Define JADE Behaviors	GAIA Interactions and Roles Models; Jade ACL Messages, Application Data Class Diagram, and Activities Refinement Table	Jade Behaviors Repository	Coding of behaviors in Jade: (1) define behaviors; (2) create state diagrams for each; (3) create constructors; (4) define behavior action, input and; (5) add behavior functionality.
Define Jade Agents	GAIA Agent and Service Models; Jade Behaviors	Java Code of Agents (in Jade)	All events should be caught in this level.

5.3 Conceptualization

The simulation approach combines….

Chapter 4 discussed the adequacy of agent-based modeling for representing response agents and coordination in multidisciplinary crisis response. However, to conceptualize the simulation model architecture, the use of agents is complemented with the use of discrete-event modeling for the crisis environment. Accordingly, this section presents the architecture of the simulation model using both an agent-based and a discrete-event simulation approach.

Combining agent-based and discrete-event simulation approaches

The use of agent-based simulation is appropriate for studying coordination in crisis response, especially when confronted with the tension between top-down and bottom-up coordination mechanisms. However, an agent-based model, while best suited for representing a crisis response organization, does not necessarily offer the best abstraction for the crisis environment itself. Other representations may be used for the objects, events and dynamics of the environment in which the agents interact. Discrete-event simulation is an approach in which events are arranged discretely, which is in line with how crisis simulations (computer-based or not) are typically conceived. For example, a description of a crisis response exercise starts with an incident and events are added in an historical fashion, as the situation is set to evolve or escalate (*cf.* CrisisSim in Chapter 3). Discrete-event modeling is well-suited for the entities that are affected by these events or which in turn generate new events. For example, environmental entities such as vehicles or infrastructure can affect the dynamics of an evolving fire incident. These environmental entities differ from the response agents in that they do not necessarily require a high degree of autonomy or interaction. It is possible to combine the benefits of both approaches in an architecture that uses agent-based and discrete-event modeling, integrating them but maintaining enough separation to preserve the qualities of each approach and enabling independent changes in the environment and the response organization.

agent-based and discrete-event modeling.

Previous research has already proven the plausibility of combining discrete-event and agent-based simulation. Classic problems of discrete-event simulation (DES from now on), e.g. the generic job shop, can be simulated as a multi-agent system (MAS from now on) (Zhou, Lee, & Nee, 2008). Other approaches aim at combining the process-oriented approach of DES and the autonomous characteristics of MAS by adding a simulator with artificial time mechanisms to study different design choices enacted by the agents (Janssen & Verbraeck, 2005). On the one hand, it is possible to bring DES concepts into MAS (Gianni, 2008). This option extends agent behaviors to support DES behaviors, such as event handling and notification. On the other hand, agent-based systems can also be built inside a DES environment (Kádár, Pfeiffer, & Monostori, 2005). In this case, communication between the agents is added as an extension to the DES model, using specifically developed agent interaction protocols.

Similar combinations have been done before.

The conceptual model of the simulation architecture keeps the discrete-event crisis environment, decoupled from the agent-based crisis response organization. An object-oriented representation of the crisis entities constitutes such environment which is affected by crisis events. Such events include a crash, an alarm, an explosion, changing of a victim state according to a life function that "schedules" an increase in severity, or the growth (and death) of the fire. The underlying DES simulator handles the events by adding them or removing them from a single event list of which all crisis objects have a reference through sharing a single DEVS (Discrete Event System Specification) simulator interface instance. This simulator is also in charge of the pseudo-random number generation, which takes numbers from a stream created according to a seed number which is different for every simulation replication. Pseudo-random numbers are used for initial placement of crisis objects in the environment, for instance influencing the density of civilians around the incident area, thus increasing or decreasing the likelihood of victims. The same stream is used to manage the animation of objects as a set of linear movements, using linear interpolation and a normal distribution.

Besides this crisis environment, a multi-agent system contains the crisis response agents to support their autonomy and be able to model different coordination mechanisms between them. Thus, it is possible to produce new crisis scenarios relying on the DES environment, while at the same time making it possible to add new agents or new agent behaviors to the MAS organization to alter the way in which the response (specifically its coordination) is carried out.

Requirements and analysis

The analysis results in:

As a prerequisite of the GAIA based analysis and part of the conceptualization of the simulation model, there was an initial phase of requirements elicitation, based on identification of response processes for a particular crisis scenario. The processes were extracted from crisis response manuals (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2003c) and the scenario was adapted from a training case used to describe the Dutch crisis response levels (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2007b). This training scenario is the same one summarized in the Vignette in Chapter 1. By using a particular scenario, it was possible to limit the number of relevant response processes, according to an additional document of guidelines (Ingenieurs/Adviesbureau SAVE & Adviesbureau Van Dijke, 2000). These guidelines were used to filter and fit the response processes to the type of crisis which the scenario belongs to. The result is a list of response procedures and the agencies involved, which serves as basis for identifying the roles for the agents. The analysis containing the response processes, decomposed into disciplinary activities can be found in Appendix A.

an environmental model,

Once the response activities have been identified, an environmental model, which in GAIA is an abstract, computational representation of the environment in which the MAS will be situated, can be designed. Following this understanding of a computational organization fits with the separation between the MAS organization and the DES-based environment. A depiction of the understanding that GAIA has of a MAS as a computational organization is shown in Figure 5-3.

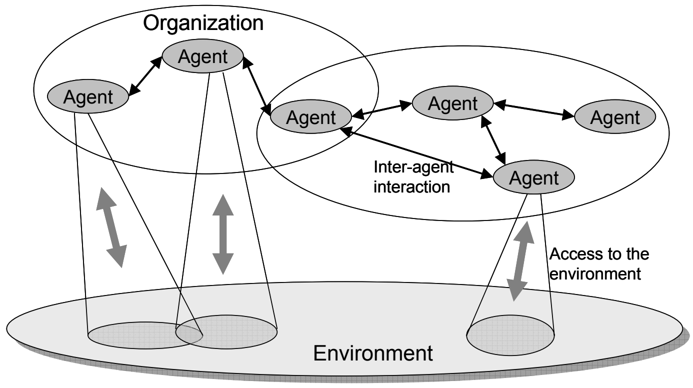


Figure 5-3 MAS computational organization, from (Zambonelli *et al.*, 2003)

The environmental model represents the entities that exist inside the DES-based environment. Although GAIA does not provide specific techniques for representing the environmental model, it can be shown as a list of resources characterized by the type of actions that agents can perform on them (Zambonelli *et al.*, 2003). Table 5-2 shows the resources for the selected crisis scenario.

Table 5-2 Environmental model resources

Resource	Type of Action
Civilian (Victim)	Changeable: response agents can read the location and state of civilians and change their location and provide assistance when they become victims.
Fire	Changeable: response agents can read the location and size of the fire. Firemen can also change the size by fighting the fire.
Vehicle	Readable: Response agents can read the location of the vehicles.
House	Readable: Response agents can read the location and size of houses, which represent an exemplar instance of infrastructure elements in the environment.
Shared data space	Changeable: In order to support mediated coordination of rescue operations, the response agents have the ability to write the location of the victim they have selected for rescue (equivalent to sending their geographic coordinates) into a centralized shared data space (SDS). Other rescuers can read this SDS to check whether the victim's location is already registered and chose another (if there is one). After assisting the victim, the rescuer removes the victim location from the SDS.

The environment is implemented as a discrete-event simulation model, where the objects (resources) are decoupled from the MAS organization, but can be accessed by individual agents, according to the permissions in Table 5-2. The events to be simulated are those related to the sequence of the escalating incident (e.g. the crash and the explosion). Such events only directly affect the objects in the environment (with the exception of the shared data space, which is not a crisis related object, but still a part of the environment), while the response agents behaviors are aimed at responding to the consequences of such events, i.e. fighting the fire and rescuing the victims.

preliminary agent roles, and

After identifying the environmental objects, the preliminary role model of the agents provides an analysis phase view of the roles and protocols in the multi-agent system, where roles are represented through permissions and responsibilities (Zambonelli *et al.*, 2003). From the basic crisis response handbook (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2003c) we can identify the following roles in Table 5-3.

Table 5-3 Preliminary agent roles

Operational first responders
Fire field agent (Fireman)
Medical field agent (Medic)
Operational leaders
OvD (Fire Municipal commander in CoPI)
OvD-G (Medical Chief in CoPI)
CoPI Leader (CL): leader of the CoPI (typically the OvD)

respon-sibilities.

Responsibilities for the previous roles are expressed in terms of *liveness*. Liveness properties describe the state of affairs that an agent must bring about, defining the potential execution trajectories through the various activities and interactions associated with the roles (Zambonelli *et al.*, 2003). Liveness properties are expressions containing activities (underlined) and protocols (activities that require interaction with other roles – not underlined). When the expressions use "x*" it means that the activity occurs 0 or more times. When they use "x‖y" it means that the activities x and y are interleaved (occur in parallel). When they use x^{ω} it means that x occurs indefinitely often. When they use [x], it means that x is optional. The following constitute the preliminary responsibilities for the identified roles:

```
FIREMAN =(AssessFire.InformFireAssessment.ContainFire)*•
         (IdentifyVictims.InformVictimLocation)*
MEDIC = (AssessFire.InformFireAssessment)*•
         (IdentifyVictims.InformVictimLocation.AssistVictims)*
OvD =   (AnalyseFireSituation.PlanContainment.CommunicatePlan.
        GetContainmentResources.DeployContainmentResources.
        SuperviseContainment)*
OvD-G = (AnalyseMedicalInformation.PlanMedicalAssistance.
        GetMedicalResources.DeployMedicalResources.InformSituation.
        EvaluateMedicalAssistance)*
CL =    CoordinateCoPI •
```

The preliminary interaction models that should result from a GAIA-based analysis are contained in Appendix A. Both the preliminary role and interaction models are revised later in design time. It is now possible to conceptualize the simulation model architecture.

Simulation model architecture

The architecture presented in this section uses the process-oriented, discrete-event characteristics of DES alongside the decentralized autonomous representation of crisis responders as agents. However, the architecture also allows for the agents themselves to be represented inside the DES model as entities: animated proxies which handle the physical interaction with the environment (after being prompted to do so by the "owner" agent). This separation is not strictly necessary, but allows the MAS and DES components of the architecture to evolve separately – this is where this approach differs from others mentioned earlier. Firstly, the same (DES-based) crisis scenario can be used as a setting to test different configurations of coordination of the (MAS-based) crisis response organization. Secondly, the same crisis response organization (MAS-based) can be tested for different (DES-based) crisis scenarios.

The simulation model architecture contains:

The architecture of the simulation model is defined as a set of interconnected Unified Modeling Language (UML) *packages* (represented as folders) that contain the *classes* corresponding to DES entities (*Environmental Model*) and MAS agents (*Agents*) respectively, in addition to a *Visualization* and an *Ontology* package. The *Ontology* package reflects the philosophy behind the FIPA agent specification (IEEE Foundation for Intelligent Physical Agents, 2009), requiring an ontology to be defined for the multi-agent system. The *Visualization* package is also used for support, in this case for providing visualization functionality to the *Environmental Model*. All four packages can be seen in Figure 5-4.

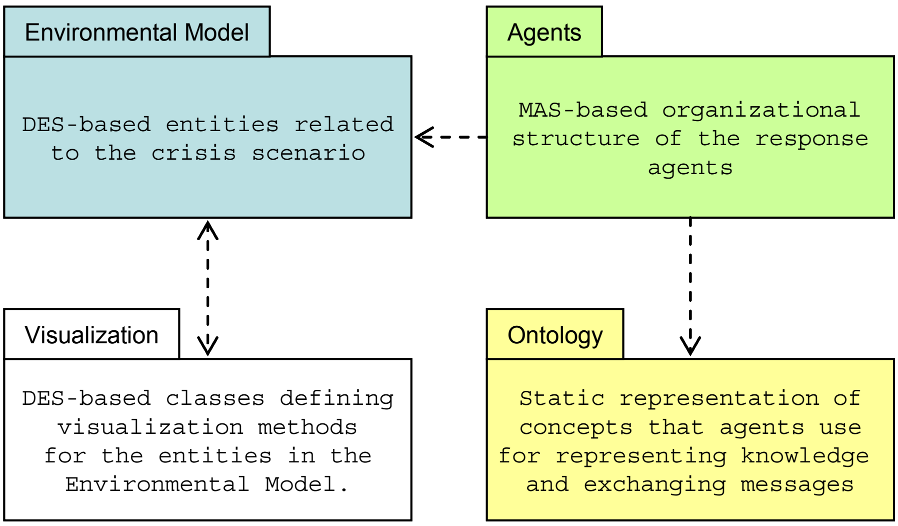


Figure 5-4 Architecture of the simulation model

The *Environmental Model* is the package containing the DES entities for the crisis scenario. In our case, the crisis scenario is the one described in the Vignette on Chapter 1, but the idea is that this should be the container for any given crisis scenario that is to be simulated. Essentially, this package is where the discrete-event model resides. All environmental entities are modeled as classes (in the object-oriented sense), which can generate or react to discrete events and which

an environmental model package,

are synchronized by the same discrete-event simulator. The *Environmental Model* contains the logic of the environmental entities, but interacts with a *Visualization* package that contains presentation methods for the simulation.

a visualization package,

The *Visualization* package contains the classes that define the visualization behavior for the entities in the *Environmental Model*. This package is added to enable further flexibility and decoupling in the architecture. While the *Environmental Model* contains the entities related to the crisis scenario (e.g. houses, vehicles, civilians), the *Visualization* package contains abstract animated or static objects that define the methods for visualization and movement when running the simulation. This allows the *Environmental Model* to be changed or extended without being attached to particular visualization implementation. Here, an important design decision on the architecture must be noted. The response agents also need to be visualized in the simulation, but there is no direct connection between the *Agents* package and the *Visualization* package. The reason for this is a choice for modeling response agents **both** as entities inside the *Environmental Model* **and** as agents in the *Agents* package. It follows that when a response agent (e.g. a fireman) exists as an entity inside the *Environmental Model* it can then extend its behavior by being associated with an animated object inside the *Visualization* package. At the same time, this responder entity will also be connected to its corresponding agent inside the *Agents* package, but the latter is independent of the visualization.

an agents package,

The *Agents* package contains the organizational structure of the MAS of response agents. The agents in this package are connected to the *Environmental Model* by having a "proxy" entity representing the physical responder inside this model. Although it is equally possible to extend the agents so that they, once instantiated, have an actual presence inside the *Environmental Model*, the design choice is to separate the MAS behavioral descriptions inside the *Agents* package from the discrete-event responders inside the *Environmental Model*. For each agent inside the *Agents* package, there will be one responder inside the *Environmental Model*. In a way, this constitutes a separation of body and mind of the response agent that enables extensions of the behavior of the agent regardless of whether it will be physically simulated in a discrete-event environment or not. Conversely, the responder entity inside the *Environmental Model* exists independently of whether it is controlled by an agent or not. In our case, the responder entity only acts when prompted by the corresponding agent in the *Agents* package, but other non-agent mechanisms (i.e. the own methods of the responder entity) could also make it move or interact with the other entities in the environment. The response agents in the *Agents* package interact with the *Environmental Model* by reading (observing) the entities in an area around the physical representation of them and can only effect changes in the environment when their physical proxy is able to do so.

The *Ontology* package is provided so that the agents comply with the FIPA specifications and can use communicative acts that use the ontology as the language for exchanging, coding and decoding messages. The ontology can also be seen as a static (and empty) representation of the knowledge of the agents, i.e. their mental model. Hence the arrow connecting the *Agents* package and the *Ontology* package flows from the agents to the ontology, which remains static. The *Ontology* package contains the ontology objects that should map to the *Environmental Model* entities, following an agent's observation. For example, there will be an ontology object for the fire as well as a fire entity in the *Environmental*

Model. However, in the *Environmental Model* the fire will have a state corresponding to the "true" state of the fire (including for example its size and location), while the fire ontology object, once instantiated inside an agent, will contain information on the fire as observed by the agent. This means that there could be additional information inside the ontological fire, such as the nature of the fire, which corresponds to a category as determined by the agent's judgment. In addition, there can also be inconsistency between the ontological fire object that the agent *knows* and the real fire entity that the agent *observes* (for example, a misperception of size). In any case, the ontology object of fire inside the *Ontology* package does not change at all, because it is a static description of a concept and not an instantiated piece of knowledge. Instantiation takes place inside each agent. Further specification of the architecture packages just described will continue from an agent-based and a discrete-event based high-level design perspective.

and an ontology package.

DES-based high-level design

As noted before, the *Environmental Model* is designed as a DES simulation model where entities are subject to events and dependent on the same time-advancement mechanism. The DES model is built on the D-SOL discrete-event JAVA-based simulation suite (Jacobs, Lang, & Verbraeck, 2002). Although at this point the model is implementation-independent, this choice makes it possible for the design to follow an object-oriented specification that fits with both the DES simulation suite and the agent-based platform. There are entities related to the emergency situation (including physical representations of the response agents); and there are generic classes defining the behavior of visualization aspects. Both are contained in the packages shown in Figure 5-5.

The discrete-event high-level design contains…

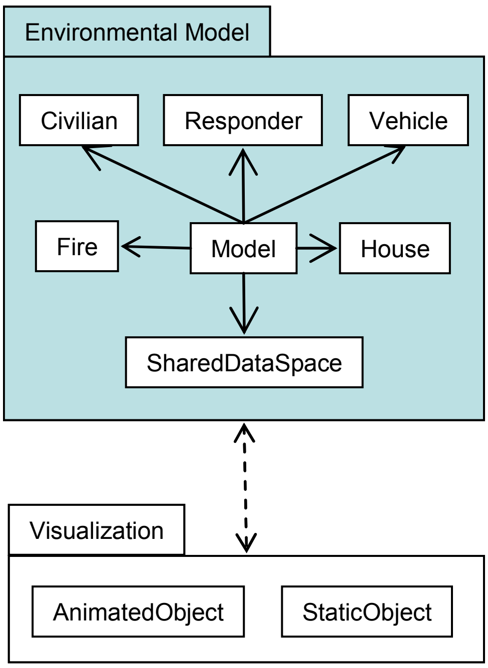


Figure 5-5 DES-based high-level design

The *Environmental Model* package contains a *Model* class where all the entities are instantiated. This *Model* class implements a *DES model interface* as defined by the D-SOL simulation suite. This provides the means for the model to be constructed with a reference to a DES simulator that is instantiated at the application level – the application itself can be managed through a utility class as in our case (not shown in the architecture) or using the interface provided by D-SOL. Once the *Model* is constructed, all environmental entities are instantiated in its context with a reference to the same simulator. In this case, those entities are implemented as the following classes: *Civilian*, *Responder* (physical proxy for the response agent), *Vehicle*, *House* and *Fire*. In addition, the *SharedDataSpace* class is used to represent a central shared data space for the agents to add victim locations for rescue and remove them after rescue. This enables the agents to coordinate their distribution in opposition to the autonomous option where the agents select a victim but mutually adjust their selection by observing whether the victim has already been assisted or not. These classes can be instantiated or deleted from the container *Model* as the crisis evolves in run-time, but can also be added or modified in design-time to define a different emergency scenario.

a D-SOL model interface,

Given that we need the response agents in the *Agents* package to communicate with the *Environmental Model*, the *Model* class "extends" a JADE agent. Effectively this means that the *Model* class is both a DES model and an agent. However, this has no influence on the DES aspects of the *Model* itself, since the agent-based behaviors are defined separately and will not be active until an agent container has been deployed. Without an agent container and an agent setup, the *Model* simply behaves as a DES simulation model. Because the *Model* is not really an agent inside the *Agents* package – in the sense that it exhibits no autonomous behavior – it only implements the standard *setup* and *take down* methods of a JADE agent. This allows messages to be exchanged between the *Model* and the agents. The *Model* then acts as a centralized gateway between the agents and the entities of the crisis environment without having to change either the implementation of the *Environmental Model* or the implementation of the *Agents*. The fact that both JADE and DSOL are JAVA-based and that the *Model* class implements a DSOL model and extends a JADE agent, allows for this simultaneous integration and separation of DES and MAS components of the architecture.

which extends a JADE agent.

MAS-based high-level design

The MAS-based high-level design corresponds to the MAS "architecture" in terms of the GAIA methodology, but will be referred to as high-level design to distinguish it from the overall simulation model architecture. The high-level design of the MAS is equivalent to the organizational structure of the system, itself a combination of the topology and control regime of the agent organization. A topology for the MAS organizational structure may be peer-to-peer, hierarchical, multi-level or composite. The topology in this case needs to combine the hierarchy explicitly designed into the professional response organizations, with the lateral relationships possible between first responders and officers. The control regime can be based on specialization or partition. In a crisis response organization (homogeneous) partitioning occurs within disciplines and (heterogeneous) specialization occurs in between disciplines. With these elements it is possible to define the *Agents* package of the simulation model architecture

The agent-based high-level design…

(Figure 5-4) which represents the high-level design of the MAS and is shown in Figure 5-6.

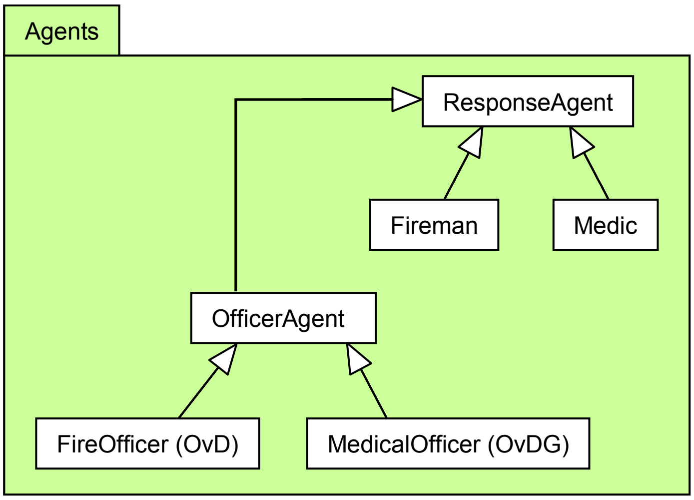


Figure 5-6 MAS-based high-level design

The *Agents* package defines the container of the classes that implement each of the agents as objects. The two main types of agents are the *ResponseAgent* and the *OfficerAgent*, both of which can be specialized into any of the crisis response disciplines. The preliminary role and interaction models can now be revised and are shown in their final designed specification in Appendix B. With this, it is now possible to switch from the implementation-independent design to one in which the agents will be implemented over the JADE framework.

contains the response and officer agents.

5.4 Model Construction

Model construction consists in making a transition from the data-void and implementation-independent design model presented in the previous section. The result is a simulation model system which has to be executed on a computer and is thus implementation-dependent. This means making the transition from the GAIA analysis and design to the GAIA2JADE process introduced in the simulation method description in Section 5.2.

Model construction results in…

Communication protocols

The first implementation-dependent step that follows the GAIA2JADE process (Moraïtis & Spanoudakis, 2006) is defining the communication protocols for the agents, through an ontology and a set of ACL messages. A domain ontology in JADE, made up of concepts, predicates and actions, describes the elements that agents use to create the content of messages (Bellifemine *et al.*, 2008). The *Concepts* are the semantic elements of the vocabulary. *Predicates* are the *communica-tion protocols using an ontology and*

structural elements, which group assertions about other elements in the ontology. *Actions* are special concepts that denote agent actions, also through composition of other ontological elements. Table 5-4 describes the domain ontology. The detailed ontology, including the specific attributes for each element can be found in Appendix B.

Table 5-4 Domain ontology

Element	Name	Description
Concept	Population	Population observed by a responder
Concept	Fire	Observed fire
Concept	Grip	GRIP level of the incident
Concept	Element	Observed physical element in the scenario (e.g. House)
Concept	Location	Location (e.g. used to propose location of CoPI)
Concept	Responder	Responder proxy in the environment, not to the agent.
Concept	Strategy	Response strategy: contains number of firemen to send to support victim rescue and other resources needed.
Concept	Time	Timestamp of observations
Predicate	Awareness	Current observation of the incident
Action	Alarm	Alarm message
Action	Plan	Response plan, where the strategy becomes an action.

Having identified the elements of the ontology, it is now possible to determine the objects inside the *Ontology* package in Figure 5-7.

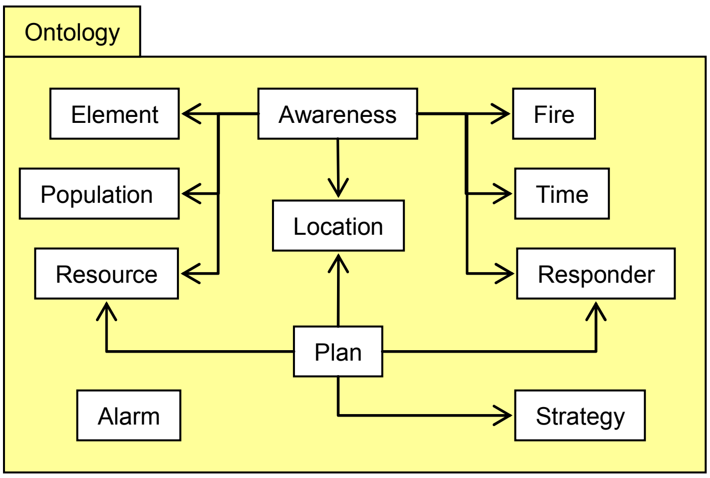


Figure 5-7 Ontology class diagram

Given the interaction model defined in the design and the above ontology, ACL messages according to FIPA (IEEE Foundation for Intelligent Physical Agents, 2009) can be defined. Table 5-5 presents the interaction protocols which group such ACL messages.

interaction protocols.

Table 5-5 Interaction protocols

ACL Messages	Sender	Receiver	FIPA Performative
Request Assessment (FIPA Query)			
Request Assessment	Officer	Responder	Query-ref
Query Not Understood	Responder	Officer	Not understood
Refuse Query	Responder	Officer	Refuse
Query Failure	Responder	Officer	Failure
Inform Assessment	Responder	Officer	Inform
EstablishCoPI (FIPA Propose)			
Establish CoPI	OvD	Officers	Propose
Accept CoPI	Officers	OvD	Accept proposal
Reject CoPI	Officers	OvD	Reject proposal
NegotiateProposals (FIPA Propose)			
Call for proposals	CL	Officers	cfp
Refuse cfp	Officers	CL	Refuse
Propose plan	Officers	CL	Propose
Reject plan proposal	CL	Officers	Reject-proposal
Accept plan proposal	CL	Officers	Accept-proposal
Inform plan status	Officers	CL	Inform
Inform plan failure	Officers	CL	Failure
AlarmResponders (FIPA Request)			
AlarmResponders	Officer	Responder	Request
Refuse alarm	Responder	Officer	Refuse
Accept alarm	Responder	Officer	Agree
Alarm request failure	Responder	Officer	Failure
Notify arrival	Responder	Officer	Inform

Agent activities refinement and behaviors

This step defines the activities refinement table, where application-dependent data, their structure and the algorithms that are going to be used by the agents are defined (Moraïtis & Spanoudakis, 2006). The *activities refinement table* is meant to

Construction follows...

with activity refinements,

specify the liveness properties of the agents, having defined the ontology. Under read and change, there is a reference to data classes (no longer environmental objects, but ontology-dependent classes). Under Description there is a top-level algorithm in pseudocode for the corresponding activity. As an example, Table 5-6 shows the activity refinement table portion for the Fireman role. The complete activity refinement table for all agents can be found in Appendix B.

Table 5-6 Activity refinement table for Fireman

Role	Activity	Read	Change	Description

Fireman	Fireman	Responder
		Location
		Element
		Fire
		Civilian
			-	**do** GetToLocation
				do NotifyArrival
				while Strategy.exit != [exit criteria]
				  do AssessSituation
				  do InformAssessment
				  while fire != null || civlians.status != victim
				    do Respond
				    do UpdateAssessment
				    do InformResult
				  end while
				end while

Fireman	Respond		Fire
			Civilian
				if assigned Fire
				  do ContainFire
				else if assigned Victim
				  do MoveVictim
				end if

and agent behaviors…

The final step implements GAIA activities as JADE Behaviors (Moraïtis & Spanoudakis, 2006). First, behaviors are defined. Second, a state diagram (UML) is provided for each relevant behavior. This helps to identify data exchanges between behaviors and to easily map them to JADE FSM (Finite State Machine) behaviors. JADE behaviors are defined from GAIA activities, through mapping activities. All GAIA liveness formulas are translated to JADE behaviors. All behaviors should inherit from the *jade.core.behaviors.Behavior* class. The FSM diagram for all of the agents is presented in Appendix B.

implemented from the bottom-up.

Implementation in Java using Jade libraries follows from the bottom-up (from simple to complex behaviors). Each of the behaviors defined in Appendix B is implemented in Java following the GAIA2JADE guidelines. Each behavior becomes an inner class within each agent and the *action()* method is where the behavior is implemented. Behaviors are arranged hierarchically according to the FSM specification. The upper level behavior corresponds to the agent herself (i.e. *FiremanBehaviour*, *MedicBehavior*, *OvDBehavior* and *OvDGBehavior*), followed by one or two additional levels depending on the agent (e.g. the *FiremanBehavior* is decomposed into simple behaviors and a complex *RespondBehavior*, which is also decomposed into complex behaviors *ContainFire* and *AssistVictim*). Implementation should be done from the simplest to the most complex. The complete resulting code (using version management) is openly accessible online at: http://code.google.com/p/crisiscoordsim/.

5.5 Vignette: Agent Communication

Table 5-5 shows the interaction protocols that agents will use for communication. However, several design decisions and counting strategies are worth noting. For every message that is sent expecting a reply (Request, Query, Propose) the *setReplyByDate* method is used to create a deadline. After this timeout (set at 3 seconds of clock time, or 3 minutes of simulated time) the replies will not be processed, avoiding the use of outdated information and preventing the agents from being blocked inside a behavior waiting for a reply that might take too long or never arrive. Despite the timeout, it will still be the case that replies received by the officers regarding individual assessments of the situation will be delayed and might provide information that is inconsistent with the real emergency (e.g. fire size or the number of victims can change). In many cases, as in a real crisis, officers will make decisions based on incomplete or inconsistent information and affected by delays in getting replies (cf. coordination issues in Ch. 1 and information quality attributes in Ch. 3).

Also influencing the way in which the experimental results are obtained is the actual moment and times that each message is counted. In Table 5-7, a summary of the messages and the way they are counted is provided.

Table 5-7 Summary of messages and how they are counted

Sender.Behavior	Description of message	Counting
OfficerAgent. Request-Assessment	QUERY (FIPA_QUERY protocol): officer requests assessment of the crisis (cyclically revised). All assessments are later merged into a single intra-disciplinary awareness of the situation.	Adds one intra-disciplinary msg. per receiver.
OvD. Multidisciplinary-Consultation	PROPOSE (FIPA_PROPOSE protocol): Fire Officer proposes shared awareness to peer officers after merging the assessment from own responders. If proposal is rejected, awareness is revised. If accepted, awareness is committed.	Adds one interdisciplinary msg. per receiver.
OvD. EstablishCopi	PROPOSE (FIPA_PROPOSE protocol): Fire Officer proposes establishment of CoPI to peer officers when shared awareness results in GRIP level of 1 or more. If more than half the peer officers accept, CoPI is setup.	Adds one interdisciplinary message per receiver.
OvD. Plan-Containment	PROPOSE (FIPA_PROPOSE protocol): Fire Officer proposes containment plan to peer officers after determining a multi-disciplinary shared awareness. This determines the need for assigning firemen to rescue if medics are insufficient.	Adds one interdisciplinary message per receiver.
OvD. Deploy-Containment	REQUEST (FIPA_REQUEST protocol): fire officer requests a number of firemen to rescue victims (as opposed to fire fighting) depending on containment plan.	Adds one intra-disciplinary msg. per receiver.
OvDG. Proposal-Response	ACCEPT_PROPOSAL, REJECT_ PROPOSAL or NOT_UNDERSTOOD (FIPA_PROPOSE protocol): Medical officer sends reply for each proposal sent by the OvD based on own intradisciplinary awareness.	Adds one inter-disciplinary msg.
ResponseAgent. SearchVictim	Indicates the use of a shared data space for distribution of rescuers from multiple disciplines among victims. Victim location is sent to SDS once victim is found or another victim chosen if location already registered.	Adds one inter-disciplinary msg.
ResponseAgent. MoveVictim	After moving victim, location is removed from SDS.	Counted as inter-disciplinary msg.
ResponseAgent. Inform-Assessment	INFORM (FIPA_QUERY protocol): ResponseAgent sends assessment of the crisis as a reply to a request from officer.	Counted once as intradisciplinary.
ResponseAgent. Message-Responder	AGREE or NOT_UNDERSTOOD (FIPA_REQUEST protocol): response agent sends replies to requests for action, which are processed cyclically and in parallel to all other behaviors.	Counted once as intradisciplinary.

Agents observe and communicate about objects in the (discrete-event based) crisis environment. A screenshot of the running simulation shows those objects in Figure 5-8.

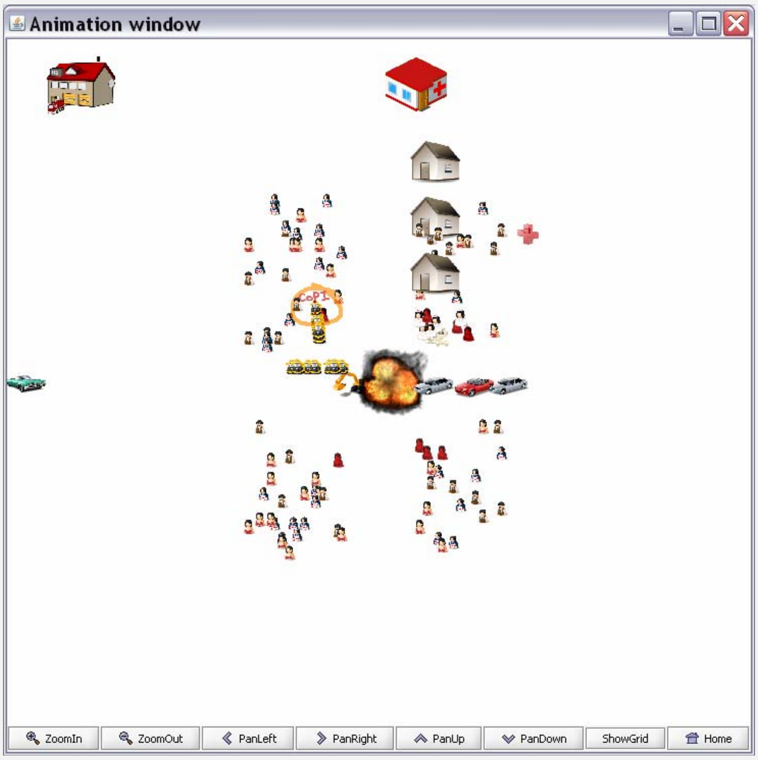


Figure 5-8 Screenshot of the running simulation

Zooming in after some time, Figure 5-9 shows the firemen dividing themselves between fire fighting and supporting the medical team with rescue.

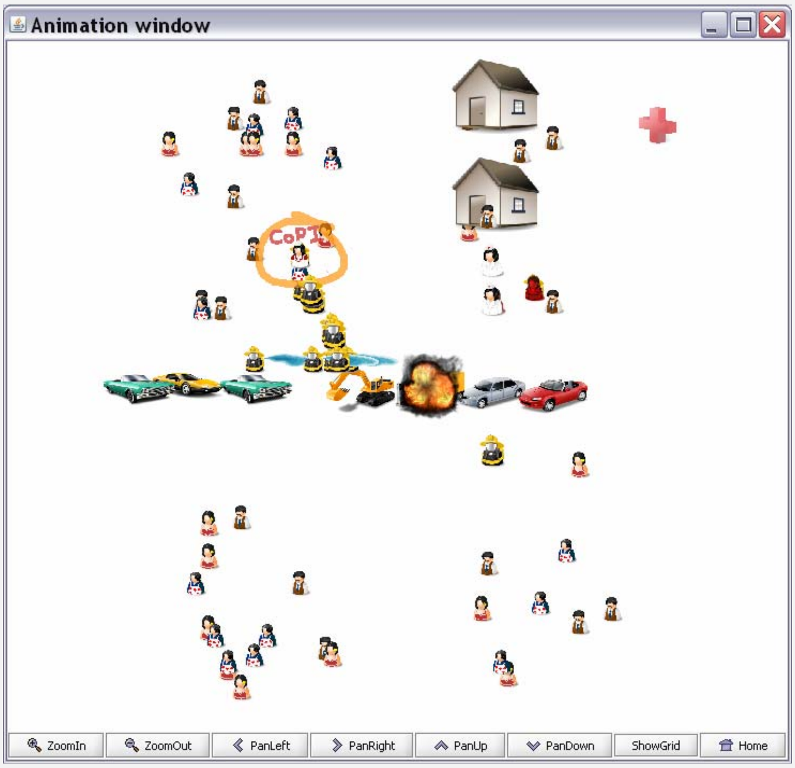


Figure 5-9 Zoomed in screenshot of the running simulation

The simulation uses icons for representing the crisis objects, shown in Table 5-8.

Table 5-8 Icons in the animated simulation

Icon	Object	Icon	Object	Icon	Object
	Fire station (StaticObject)		CoPI team (StaticObject)		Fireman Proxy (Animated-Object)
	Hospital (StaticObject)		Civilian (StaticObject)		Medic Proxy (Animated-Object)
	House (StaticObject)		Victim (StaticObject)		OvD Proxy (Animated-Object)
	Vehicle (Animated-Object)		Victim collection (StaticObject)		OvDG Proxy (Animated-Object)

Agents communicate about the objects in the environment by coding their observation using the ontology (see Table 5-4). A useful feature of Jade is enabling a visualization of communication between the agents, by using a *sniffer* agent to record, visualize and open every message sent or received by the agent(s) being *sniffed*. Figure 5-10 shows a snapshot of this where examples of a Request, Query and Propose protocol are seen in action. The arrows represent messages and label their type.

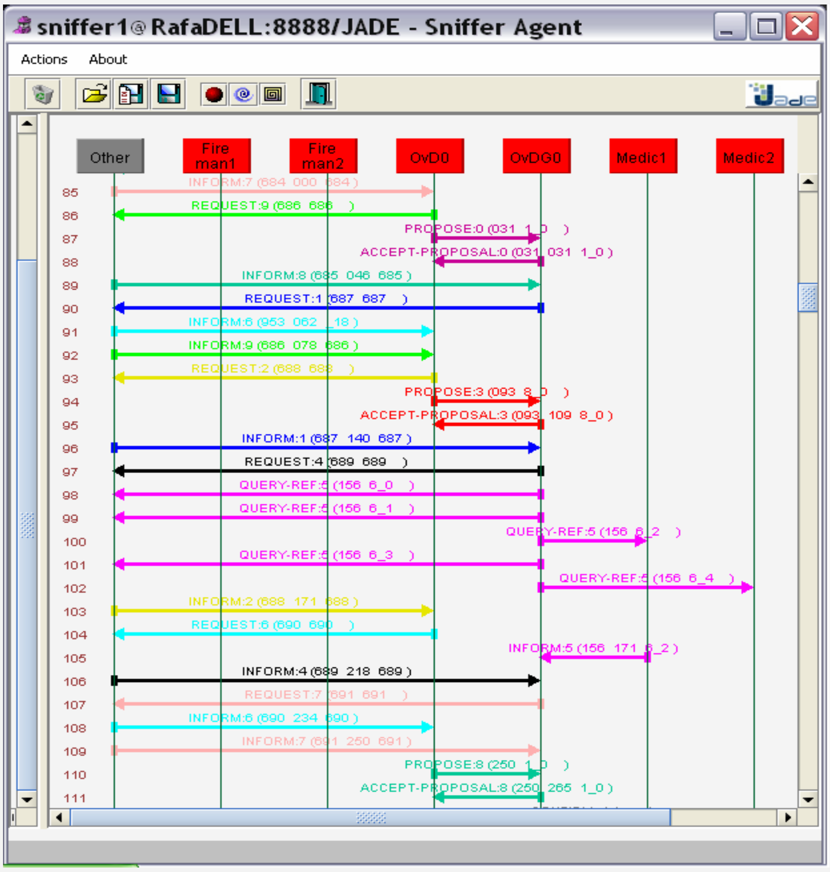


Figure 5-10 Screenshot of message exchanges for a selection of agents

In addition to the type of ACL message that the message corresponds to, the *sniffer* also shows each message ID and a color coding which helps identify conversations between the agents. For example, each Propose message sent by OvD0 to OvDG0 in Figure 5-10 is immediately followed by the acceptance of the proposal using the same conversation ID and color; or the Query-ref message (ID 156) sent from OvDG0 to Medic1 is replied to with the corresponding Inform reply also using the same ID and color.

By double-clicking on a message (arrow) it is possible to see the detailed content and metadata attached to it, following the ontological structure defined earlier in this chapter. In Figure 5-11, a request for assessment and its corresponding reply are shown next to each other. On the left-hand side of Figure 5-11 a query message sent from OvD0 to Fireman1 is shown. Besides the sender and the message and conversation IDs, the content simply shows "(Awareness)" which should be interpreted by the received as a query into the Awareness ontological predicate as defined in Section 5.4. On the right-hand side is the corresponding reply (an inform ACL message) which wraps in the content all observations made by Fireman1 regarding the Awareness predicate including a point of view (location of the Fireman) and a timestamp.

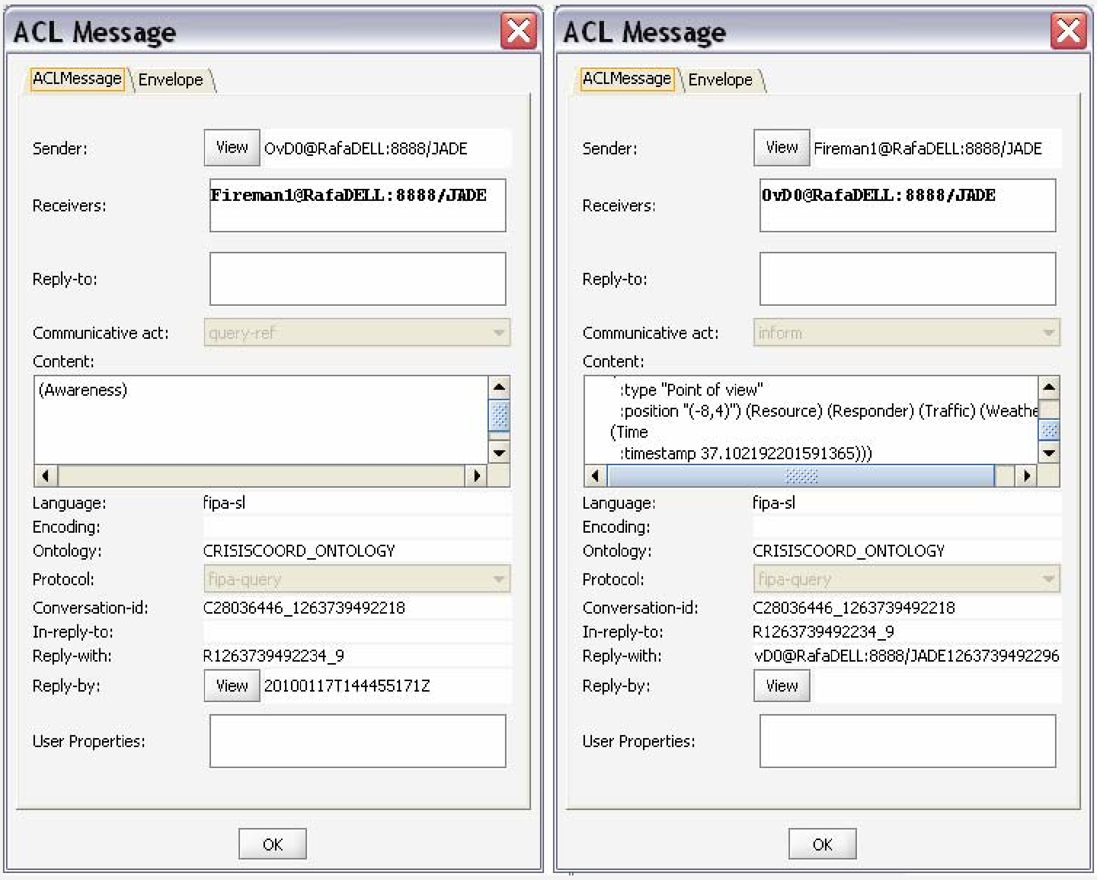


Figure 5-11 Screenshot of a query message and its reply

6 Validation and Experiments

6.1 Introduction

Chapter 4 established the benefits of using agent-based simulation in the domain of crisis response. Simulation can be used to provide a more economical method of testing contingency plans and practicing coordination between different response agencies. Agent-based simulation in particular can be used to define behavior down to the individual agent level, which is useful in modeling emergency response to a disaster. This motivates the choice behind using agent-based simulation for the study of coordination in crisis response, but implies challenges in terms of validation. Such challenges include scarcity and inconsistencies in actual data for comparison (Robinson & Brown, 2005) and the lack of a straightforward process for interpreting simulation data (Jain & McLean, 2003).

Validating a crisis simulation in design science…

In terms of the research approach, validation as part of design science research in information systems (DSRIS) is contingent on three assumptions or choices: the role of theorizing, the type of theory developed and the relationship between theory validation and artifact evaluation. In Chapter 1 it has already been established that there is a theoretical contribution, which is made up of constructs, models and methods, following Gregor and Jones (2007).

is contingent on the role of theorizing,

The third assumption or choice refers to the relationship between artifact evaluation and theory validation. In general, DSRIS emphasizes artifact evaluation over theory validation (Hevner *et al.*, 2004; Kuechler & Vaishnavi, 2008; March & Storey, 2008; Peffers, Tuunanen, Rothenberger, & Chatterjee, 2007). Any artifact resulting from DSRIS should be assessed against a criteria of value or utility (March & Smith, 1995). But when there is a theoretical contribution as well (especially one composed of non-instantiated artifacts in the form of constructs, models and methods), the relationship between artifact evaluation and theory validation depends on the epistemological underpinnings of the research.

and on the relationship to artifact evaluation.

From a pragmatist position, an artifact's utility can be assessed to validate the underlying theory. This follows the premise that theories are intended to correspond to reality, but reality cannot be directly apprehended – we only have perceptions and representations – so we need to prove the effectiveness of theories through practical applications (March & Smith, 1995). This understanding of validation corresponds to the pragmatist philosophy according to which truth is utility or "what works in practice" (*ibid.*). In this view, the evaluation of the artifact corresponds to the validation of the truthfulness of the design or utility theory that it embodies (Venable, 2006; Walls *et al.*, 1992).

Pragmatist evaluation implies validation, Assuming this pragmatist view of validation through artifact evaluation may be problematic for the following reasons. While acceptance of the artifact might be seen as a conventional way to validate prescriptive knowledge, such acceptance is not an inherent aspect of the artifact, because the artifact might be accepted years after its construction or because it is weakly linked to the underlying theories (Iivari, 2007). In addition, validation through pragmatic success should still recognize that even if the theoretical propositions survive the empirical utility test, this status of being valid is always tentative and temporary until refuted (Lee & Hubona, 2009). The first known problem with this kind of falsification approach is that if the theory is falsified in the future, a researcher can still invoke auxiliary hypotheses to defend it (Lakatos, 1978). For example, the lack of utility of an artifact can be ascribed to misuse rather than invalid theoretical assumptions. Moreover, within DSRIS a plausible but unsuccessful artifact suggests contextual limitations rather than disconfirmation or falsification; and in any case the relation of a designed artifact to theory is extension and refinement, rather than disconfirmation (Kuechler & Vaishnavi, 2008).

but is problematic.

Chapter 1 has already established interpretivism as an alternative epistemological choice for DSRIS. An interpretive epistemology does not emphasize practical relevance (assessed through utility) over rigor, but rather considers a DSRIS contribution as requiring both relevance and rigor (Niehaves, 2007). Rigor is achieved firstly through the effective and transparent use of existing research (from the knowledge base) (Hevner *et al.*, 2004). Thus, an important part of validating a DSRIS contribution lies in clearly documenting the construct definitions, the model descriptions and the methodical choices used in building the artifact. The resulting transparency should: (1) clarify the practical problems that motivate the artifact's construction; (2) provide an understanding of existing comparable artifacts; (3) explicitly and clearly describe any metaphors or analogies used in building the artifact; and (4) present the underlying kernel theories that were used (Iivari, 2007).

Interpretive validation addresses rigor and

Interpretive validation is not confined to strict means-ends utility, avoiding the potential shortcomings of pragmatist evaluation discussed above. From an interpretive stance, using a strict means-ends evaluation ignores that goals are often not clearly delineated and that the artifact may have unintended consequences (Iivari, 2007). The means-ends relations can be modified in an experimental setting so that unintended consequences and potentially competing assumptions can be tested in advance. Validation then becomes less about *ex ante* utility assessment and more about the ability of the instantiated artifact to represent the underlying theoretical constructs and its ability to provide insight into (or enrich the understanding about) the phenomenon of interest. This fits with the premise that any DSRIS artifact be tested in laboratory and experimental situations as far as possible, before testing in real situations (Iivari, 2007). It also fits the DSRIS premise that design is science when the design is aimed at instruments to test theories (Walls *et al.*, 1992). Indeed, the artifact itself can be used to test different theoretical assumptions and their consequences, especially since it is an agent-based simulation (Klabbers, 2006), which brings us to discuss validation from the point of view of simulation.

relevance.

Dual nature of simulation in design science

A pragmatist use of simulation within DSRIS is aimed at supporting the artifact's evaluation by supplying an artificial setting for testing its potential utility. An example of this can be found in Chang (2008), where two theories (prospect theory and mental accounting) are combined into an artifact (a pricing system) and evaluated for perceived utility through simulation (using performance measures). The simulation results reveal that the prices obtained are superior to those obtained through pricing systems based on expected utility theory, thus demonstrating the value of the theory embedded in the artifact as compared to the existing approach. Another example also uses a simulation-based evaluation to determine the (potential) value of an artifact (Muntermann, 2009). In this case, the artifact is a prototype of a mobile financial notification decision support system (DSS) based on underlying forecasting models. Since it is a prototype, market adoption lies potentially in the future and thus *ex ante* evaluation is needed. Simulation provides the setting for empirically testing hypotheses about the value of the DSS on the basis of historical and artificial data. Both examples follow the pragmatist view that utility ultimately determines the value of the artifact (and of the underlying theory) and simulation is used to determine this (potential) value.

Simulation can be used for utility evaluation...

In our case, the simulation model is built inside the *Design Cycle* to enable testing different theoretical assumptions by experimenting with different configurations of coordination mechanisms under different environmental conditions. This follows the premise that an agent-based simulation model can be used to operationalize theoretical constructs and can be used to extend and refine the theory by subjecting the model to different experimental conditions (Davis *et al.*, 2007). It also fits with the interpretive view of validation from a DSRIS perspective. Simulation is used with the dual purpose of instantiating the constructs, methods and models obtained in the *Rigor Cycle* while at the same time enabling experimentation with those same theoretical elements. This is consistent with Simon's view that simulation can provide new knowledge by working out the implications of premises or assumptions, or by using simplified models in which new aspects arise out of the organization of the parts (Simon, 1996, pp. 15-17). According to Kriz and Hense (2006), simulation can be used to bridge the gap between natural science and design science, precisely due to this dual position.

and theory development.

The simulation model presented in the previous chapter can be used to gain insight about the potentially usefulness of certain coordination mechanisms (as in the pragmatist use of simulation in DSRIS). In particular, it is of interest to see whether and under what conditions a "bottom-up" coordination mechanism can outperform a "top-down" mechanism in terms of the success of the response activities and coordination costs. But in addition, by subjecting the simulation model to different experimental conditions, it is possible to obtain simulated data where no real data is available. This should increase the insight on the phenomenon of coordination in crisis response by enabling inspection not only of performance metrics, but also of conversations between response agents, including the type and content of messages exchanged (as in the Vignette on Chapter 5). Nonetheless, the validity obtained from transparently applying the theory (abstract artifacts) in building the simulation model (instantiated artifact) and from using the latter for feeding back on the theory does not preclude the validation of the model.

But the simulation model must be validated.

Validation of agent-based simulation models

Without a "real" system for comparison,

Simulation model validation is equivalent to substantiating that the model, within its domain of applicability, behaves with satisfactory accuracy consistent with the study objectives (Balci, 1994). In terms of DSRIS, the domain of applicability and the study objectives are determined by the *Relevance Cycle*, but "accuracy" is where we encounter problems. The fundamental difficulty in validating both simulation models and scientific theories has to do with the problem of induction; that is, inferring from observations of a real system that the model (or theory) captures essential structures and parameters of said system (Kleindorfer *et al.*, 1998). The simplified assumption is that any deviation from the real world output is a result of errors that diminish the model's validity. However, design should be aimed at changing existing situation into preferred ones (Simon, 1996), so deviation from the "real world" is precisely what we are aiming for. Moreover, there is a difference between predictive simulation models (where accuracy is fundamental) and exploratory simulation models for gaining insight.

validating an agent-based model cannot be done…

Validation in agent-based simulation is especially challenging given the relative novelty of the approach. A recent survey of published research pointed at a staggering 65% of agent-based models which are incompletely validated and 29% which are not validated at all (Heath *et al.*, 2009). This is especially the case for models whose purpose is exploratory rather than predictive (*ibid.*). For exploratory models there is no real system or it is poorly understood and the aim is to increase understanding and/or develop theoretical insights. Such theory-building stems from a particular class of research question. While scientific questions are typically positive (explanatory) or normative (prescriptive), somewhere in between lay questions about what is plausible (what might be), and for which simulations are particularly useful (Louie & Carley, 2008). Agent-based simulations address this "what-if" as in other simulation approaches, but also deal with the interaction between local and global, micro and macro, individual and emergent behavior, and structure vs. chaos (Davis *et al.*, 2007; Louie & Carley, 2008; Macy & Willer, 2002). The consequence is that model validation can no longer be understood simply as how close the computed behavior is to the "real" answer, because there is no "real" answer" when we are dealing with "what-if" analysis. In this case, face-value expert validation often takes the place of quantitative or statistical validation techniques (Dooley, 2002; Klügl, 2008).

through traditional methods; but rather by…

Agent-based modeling represents a new approach to simulation for which traditional validation methods are not always applicable (Louie & Carley, 2008). This creates a challenge for validation of agent-based simulation and is the source of much of the criticisms that it receives as a research method. Such criticism, however, arises from a different perspective on the use of simulation. According to Louie and Carley (2008), when the criticism surrounds the lack of real-world data for grounding the simulation model, the reply should be that the purpose of the simulation may not require data (in fact, this might be why simulation is needed) or that this does not preclude systematic and formal attempts to understand how a system behaves. Against the prospect of not being able to use traditional validation techniques, they reply that sensitivity analysis can still be employed to determine how individual factors influence emergent system behavior.

Sensitivity analysis is a useful method for validation of agent-based models which requires less data and can show whether factors have the expected effects (Louie & Carley, 2008). Sensitivity analysis will be used to generate a set of experiments that can be employed to determine the effect of individual factors on global behavior. In addition, using expert face validation is a common way of replacing empirical validation when there is no real system for comparison (Klügl, 2008). A combination of face validation and sensitivity analysis can thus provide an alternative when objective techniques are not possible (Louie & Carley, 2008). Indeed, we will use the results from the sensitivity experiments in order to get validation of the plausibility of the results and effects.

expert validation and sensitivity analysis.

6.2 Verification and Validation

From the point of view of design science research validity, this chapter stated the importance of clearly documenting construct definitions, model descriptions and methodical choices in building the artifact, as summarized in Table 6-1.

Documenting constructs, models and methods…

Table 6-1 Constructs, models and methods used in building the artifact

Coordination	Chapter 1, coordination issues in crisis response. Chapter 2, the I-P view of coordination.
Coordination dependency	Chapter 2, Fit, flow and sharing dependencies.
Coordination mechanism	Chapter 2, standards, mediation and mutual adjustment.
Emergence	Chapter 4, emergence in complex adaptive systems and crisis response.
Emergent coordination	Chapter 4, emergent coordination in multi-agent systems.
Agent	Chapter 4, agents as a unit of representation for emergence, coordination and crisis responders.
Simulation model architecture	Chapter 5, architecture of an agent-based response organization and a discrete-event crisis environment.
Agent-based high-level design	Chapter 5, high-level model of the crisis response organization and the ontology used for communication.
Discrete-event based high-level design	Chapter 5, high-level model of the crisis environment.
Agent FSM model	Appendix B, Finite-State Machine representation of the agents' behaviors.
Simulation method	Chapter 5, method for developing the model.
MAS analysis and design method	Chapter 5, Gaia as a method for analysis and design of multi-agent systems.
MAS construction method	Chapter 5, Gaia2Jade process for transforming Gaia analysis and design into Jade-dependent software code.

Documenting the constructs, models and methods in Table 6-1 contributes to answering the four questions regarding the transparency of a design science research contribution: (1) practical problems, (2) comparable artifacts, (3) metaphors or analogies, and (4) kernel theories (Iivari, 2007). The practical problems (1) that motivate the artifact's construction are made explicit in the discussion of coordination and emergence in the field of crisis response. In addition, the case studies in Chapter 3 also contribute empirical content to those issues and the role of ICT, which suggest an opportunity for building an artifact that enables the study of coordination in particular crisis scenarios and its potential use as a testbed for experimenting with ICT support of coordination in a lab setting.

contributed transparency of practical problems,

Comparable artifacts (2) are first mentioned in discussing coordination on Chapters 1 and 2. The types of ICT that can support coordination during a crisis are listed in Chapter 1 and the role of ICT is later revised in the end of Chapter 2. Chapter 3 then goes on to discuss specific instances of ICT systems at use in the Port of Rotterdam for supporting crisis response. Finally, Chapter 4 points at the use of agent-based simulation for studying and supporting coordination in crisis response, mentioning previous examples of similar simulations that have been published. It is worth noting that opting for a simulation approach is in part a result of this exploration, which suggests that there is a wide array of available tools but a gap concerning their actual benefits during a crisis. Simulation enables gaining insight in the contextualized uses of ICT and provides a setting for testing them prior to their release in the field.

of comparable artifacts,

The metaphors and analogies (3) that went into the construction of the simulation model center on the discussion of emergence and emergent coordination in Chapter 4. Agents have been widely adopted as an adequate unit of analysis of emergent behavior and as a natural way to represent crisis response agents. In addition, during model construction it has been mentioned that the responder is divided into three different but complementary representations. The agent as such (response agent) is analogous to the mind of the responder and is used to model its behavior and communication. The responder proxy inside the discrete-event environment is analogous to the body of the responder and is used to model its movement and physical interaction with other environmental objects. The responder inside the *Ontology* package is analogous to the concept of 'responder' that the response agents use to communicate about each other. This last conceptual responder is an empty container and is filled with observations made by a response agent of one or more responder proxies (e.g. their location).

of metaphors and analogies,

The kernel theories (4) that were used for building the artifact are the information-processing view of coordination in Chapter 2, extended with constructs form complex adaptive systems and multi-agent systems in Chapter 4. While the first focuses on dependencies and the corresponding mechanisms that can be designed to manage them, an agent-based perspective focuses on the individuals that need to achieve coordinated action through a combination of bottom-up and top-down mechanisms. In particular, the kinds of coordination mechanisms that went into the construction of the simulation model used the information-processing categories, while at the same time being attached to the model of the agent organization, the agents' behavior and its communication. Standard coordination mechanisms are present in the use of standard FIPA agent

and of kernel theories.

interaction protocols; in addition, each agent is modeled as a finite state machine, where the states are derived from standard crisis response manuals. Mediation is reflected in the organizational structure of the response agents, based on the multidisciplinary hierarchical organization defined in the same manuals. In addition, two specific cases of coordination are left variable between mediation and mutual adjustment (autonomy) as the experiments will show.

As a software product, the simulation model was also documented in the analysis, design and construction stages, contributing to transparency and repeatability. Version control and management was carried out and each subsequent version of analysis and design documents labeled along with the main changes that went into it. In addition, the result of the analysis and design were presented in two separate conferences (including academics and practitioners) and published in academic paper formats both for the conference and for two subsequent journal versions. Finally, discussions of the architecture were carried out with experts from industry to establish its plausibility, novelty and consistency. It is worth noting that through these discussions the issue of scalability and synchronization surfaced as a result of the combination of the agent platform with a separate simulation engine. Indeed, while scalability might be a problem for a large number of agents, no impact on performance was found for the current size of the simulation and elsewhere the scalability and performance of the Jade platform have already been evaluated (Cortese, Quarta, & Vitglione, 2002). With regards to synchronization, no problems were encountered due to the inherent capacity of agents to asynchronously process messages and the fact that physical interaction was kept separate trough the use of a responder proxy.

Documenting the software process and code…

In terms of the software program, the code was documented from day one and followed style patterns for easier readability, modularity and maintainability as well as contributing to the correctness and consistency of the simulation model. Following the criteria for judging agent-based simulation research proposed by Lazer and Friedman (2007) the code was made openly available online (see section 5.4). As with the analysis and design documents, changes to the program code were also documented in a separate log file where each decision and change is documented. In addition, subsequent revisions or versions of the code are published incrementally using a software version management system.

enabled sharing…

Besides the debugging capabilities offered by using the Eclipse Integrated Development Environment, the open code was made available to a US-based software developer interested in the model, whom the researcher did not know beforehand. He inspected the code and pointed out a couple of errors and several warnings, which were duly corrected. In addition, by deploying the simulation independently and without a manual, this provided evidence of the relative ease of use, sufficient documentation and portability of the simulation model.

and inspection, among others.

Expert validation

Expert face validation can replace empirical validation where there is no real system or data for comparison by asking experts, based on their estimates and intuition, whether the conditions represented in the model produce the expected outcomes reasonably, as a form of plausibility checking (Balci, 1994; Klügl, 2008; Louie & Carley, 2008). This should contribute an expert assessment of the

Expert validation was done…

plausibility of the simulation model results while at the same time providing some evidence of the level of understanding that the experts have of the model and its results.

through animation assessment and

Face validation was carried out using two techniques: animation assessment and output assessment (Klügl, 2008). In an animation assessment a human expert assesses the animation of the simulated system to determine whether in his or her opinion it behaves reasonably like the original system (i.e. the plausibility of the fictitious crisis scenario and the response behavior). A corresponding set of questions is designed to measure this opinion, asking whether the animation is on the appropriate level of detail, whether it displays all relevant dynamic aspects, and whether it shows the development of the simulated system from a birds perspective (Klügl, 2008). In addition to those, some questions were designed regarding the specifics of the simulation, i.e. initial conditions and their visualized effects. All animation assessment questions are shown in the first part of the questionnaire that can be found in Appendix C.

output assessment.

For the output assessment, the results of running the simulation under different conditions (sensitivity analysis) were averaged so that the human experts could check the plausibility of the absolute response values as a result of the initial configuration of the factors. The questions designed for the assessment, ask about the specific effects on response time, number of messages, victims and fatalities, as well as the effect of changing the coordination mechanisms. This refers to the second part of the questionnaire in Appendix C.

An on-line evaluation using…

Both techniques were applied in two settings: and online evaluation and an in-depth interview. For the online assessment a webpage was created containing a set of four animated scenarios corresponding to four different coordination setups after a short introduction to the simulation model. A fifth animation was included to show the dynamic message exchanges between the agents (as in Figure 5-10). In addition, the graphical results of the averaged simulation runs were also provided, along with a link to the complete dataset of experimental results. To further contribute to the openness and transparency that are a fundamental aspect of this validation, the webpage also linked to two openly available conference papers describing the simulation model development and architecture, as well as to the open source program code of the simulation model. Finally, the webpage offered a link to an online questionnaire with the set of questions regarding animation and output assessment contained in Appendix C.

academics and practitioners was …

The list of experts for this online evaluation was obtained during the 2009 International Conference on Information Systems for Crisis Response and Management. The simulation model architecture was presented in the track on Intelligent Systems and participants were asked to sign up to express their interest in participating in the evaluation (as well as gaining access to the code). Once the webpage was ready, the list was checked and out of the original twenty, seventeen were confirmed. These seventeen are all working in (agent-based) simulation and/or intelligent systems for crisis response. Thirteen of those experts work in universities in the US and Europe, while the remaining four work in industry (three in Europe and one in China). By e-mail, the experts were individually invited to visit the webpage and fill in the questionnaire.

The online evaluation was complemented by interviewing a crisis manager from the Port of Rotterdam (PoR) with extensive experience not only in crisis response in but also in training, evaluation and introduction of new technologies in this same context. The techniques of animation and output assessment were applied using the same multiple choice questionnaire, but an additional set of open questions was also used, which corresponds to the third part of the questionnaire in Appendix C. These additional questions refer to the understanding and insight that can be obtained from the simulation model. Although the objective of the validation, as said earlier, is not assessment of the potential utility of the model, through the interviews it was also possible to get some feedback regarding this issue as a way to inform subsequent design cycles and provide further evidence of the understanding of the underlying model.

complemen-ted with an interview.

The setup of the evaluation interview consisted of two parts. In the first part of approximately one half hour the simulation model was introduced, emphasizing the architecture and then going into a demonstration of the same animated scenarios as those used in the online evaluation. The animated message exchanges were also shown, opening up several individual messages to exemplify the content. The rest of the interview of approximately 30 to 40 minutes was used to pose the open questions and so the expert could individually fill in the multiple choice questionnaire, i.e. the first two parts of Appendix C.

Evaluation results

The multiple choice questions were posed as statements to be judged by the experts using a 5-point Likert scale: (1) strongly disagree, (2) disagree, (3) neither agree nor disagree, (4) agree, and (5) strongly agree (5). Response categories in Likert scales have rank order, but the intervals between values cannot be presumed equal; accordingly, Likert scales fall within the ordinal level of measurement and mean and standard deviation are inappropriate statistics (Jamieson, 2004). Alternatively, we can use the median and interquartile range (IQR) to obtain a more appropriate representation of the central tendency and variability of the responses. The median determines the mid point separating the lower and higher halvess of a sample – and there is no need to use the mean of two potential medians in our case, because we have a sample with an odd number. The IQR overcomes the dependency on extreme values that other variability measures have by determining the difference between the third and first quartiles, i.e. the range for the middle of the data (median) (Anderson, Sweeny, & Williams, 2008, p. 92).

Results are analyzed with median, IQR, and…

The results for all 12 questions as shown in Table 6-2. The table includes the count for each category, the median and the IQR. In addition, the table provides the proportion of positive responses (either 4 or 5 in the scale) for each question. This establishes the percentage of responders that scored the question (statement) with either agreement or strong agreement.

proportion of positive responses.

Table 6-2 Evaluation results

	Question	SD (1)	D (2)	N (3)	A (4)	SA (5)	Median	IQR	(4,5)/ Total
The animations show…	1. Birds perspective of the emergency and the response	-	-	2	6	3	4	1	0.82
	2. Global effect of changing number of civilians	-	1	1	6	3	4	1	0.82
	3. Global effect of changing number of firemen	-	-	3	7	1	4	1	0.73
	4. Global effect of changing number of medics	-	1	5	5	-	3	1	0.45
	5. Global effect of changing coordination mechanisms between responders	-	1	4	5	1	4	1	0.55
	6. Appropriate level of detail	1	6	-	4	-	2	2	0.36
	7. Easily detectable relevant dynamics	-	4	4	3	-	3	2	0.27
Experimental results show…	8. Plausible response times	-	1	6	4	-	3	1	0.36
	9. Plausible number of messages	-	-	7	4	-	3	1	0.27
	10. Plausible number of victims	-	-	4	7	-	4	1	0.64
	11. Plausible number of fatalities	-	-	6	5	-	3	1	0.45
	12. Global effect of changing coordination mechanisms between responders	-	-	4	5	2	4	1	0.64

Question 1 refers to the global "birds" perspective that the animations provide, as a way to judge one of the benefits of using agent-based simulation. The high median (4) and proportion of agreements (0.82) for this question indicate that the experts agree that the simulation provides a view of the global aggregate behavior of the system. Such behavior is then judged in terms of individual factors in Questions 2-5, which ask about the global effects of changing the number of civilians, firemen, medics and coordination mechanisms, respectively. With regards to the number of civilians (Question 2), we find a positive assessment from the experts (same median and agreement proportion as Question 1). In the case of the number of firemen (Question 3) the replies are also positive, albeit with a slightly lower proportion of agreement (0.73). With respect to the initial number of medics (Question 4) we find a neutral assessment (median of 3) and a 0.45 proportion of agreements, though the data shows that this is due to an equal number of agreements and neutral answers, with only one disagreement. In terms of coordination mechanisms (Question 5), the experts mostly agree that changing them produces a global effect on the system by looking at the animation (median of 4); however, the proportion of agreements (0.55) while still being the majority is lower than for Questions1, 2, and 3, given that there are 4 neutral answers and just one disagreement.

Results from the anima-tion assess-ment and….

Questions 6 and 7 relate to the level of detail and dynamics of the crisis scenario as observed in the animation. Though the simulation model was not built with detail or realism as a main goal, the interpretive approach to validation should also aim at pointing out the opportunities for improving the model in subsequent design cycles. Question 6 shows negative responses regarding the level of detail of the animations (median of 2, which is the lowest for the whole set of questions, despite 4 agreements as indicated by the IQR of 2). This is often a consequence of using a "birds perspective" in which details are abstracted to show global system behavior. As the conceptualization of the simulation model showed, the objects and types of responders were kept to a minimum in order not to introduce additional degrees of freedom to the exploration of coordination mechanisms. Question 7 asks about the relevant dynamics in the system, in order to assess whether important time-dependent aspects are easily detectable in the animation. Table 6-2 shows a neutral median (of 3) and a relatively high IQR (of 2), indicating insufficient evidence either way. As with the level of detail, this is due in part to the effect of "hiding" some aspects from the animation.

Moving onto evaluation of the experimental results (Questions 8-12) we can see that although only one disagreement on the plausibility of the results was found (for Question 8), the level of neutrality was significant for Questions 8 (about the resulting average response times) and 9 (about the average number of messages), resulting in medians of 3 and a relatively low proportion of agreements (0.36 and 0.27, respectively). During the interview with the expert in the PoR, it was suggested that this might be due to the fact that these values are really "unknown" because of the diverse and uncertain nature of crises, or of the lack of reliable log data. He added that it depends on the definition of response time, since some responders will remain longer than others. It is worth noting then that this response time refers to the overall response which is only over once the fire has been extinguished and all victims have been rescued. In terms of the number of victims (Question 10) there was overall agreement (median of 4 and proportion

the output assessment support the model's ability to …

of agreements of 0.64). When considering the fatalities (Question 11), the results were more neutral (median of 3, proportion of agreements of 0.45) with no disagreement. In addition, results show the effect of changing coordination mechanisms, according to the positive responses to Question 12 (median of 4 and proportion of agreements of 0.64). This supports the plausibility of using the simulation for comparing the effects of such coordination mechanisms.

produce plausible effects using different coordination mechanisms.

Overall, the results from the evaluation indicate agreement with the model's ability to produce global behavior which shows the effect of changing the number of civilians and firemen as well as the coordination mechanisms. The more neutral tendency with respect to the number of medics is something that will be analyzed with metamodeling. For the second part of the questionnaire, the experimental results are deemed plausible in terms of the response variables, albeit with a relatively high level of neutrality for response time and number of messages. The results also show the effect of the tradeoff involved in agent based simulations where having a global aggregate perspective on the system might diminish the level of detail and the perception of dynamics at the local level.

The interview addressed the model use for planning,

In addition to the questionnaire, an interview with a crisis manager in the Port of Rotterdam provided additional remarks regarding the simulation model and its potential usefulness (see the third part of the questionnaire in Appendix C). When asked about the potential value of the simulation model in the planning of crisis response coordination strategies (Question 13), the expert answered positively. In his opinion, the simulation seems useful and offers a novel approach that could be used previous to training to help crisis response planners understand the implications of different coordination strategies as related to the scale of the incident and the response organization. He suggested exploiting the simulation as a serious game and setting objectives before "playing" so that the planning process can benefit not only from the simulation but from the interaction with users which could provide additional insight in debriefing sessions.

for training,

In terms of the potential use of the simulation model for training responders and leaders on different coordination strategies (Question 14), the expert agreed that it can help in getting an "inside idea" about the different coordination strategies and how they are achieved through message exchanges. He also thought that the level of interactivity and detail could be enhanced to integrate the model into some of the training capabilities already in use in the PoR. Indeed, he pointed out that they have "become used to" having 3D animations as part of their computer-based training. Moreover, such animations typically involve first-person perspectives of the crisis situation (akin to what is found in first-person shooting games). He recognized the value and novelty of being able to have a global view of the incident, which no one really has during a crisis. This enables getting global insight about the coordination of the response, but could also be adjusted according to trainee profiles, to provide additional, limited views of the crisis.

In terms of using the simulation model as a testbed for assessing coordination support tools prior to field testing (Question 15), he responded positively. In fact, he went further in pointing out that it could also be used for evaluating "currently used" ICT, not just new tools. This would be possible in his opinion by mapping the content of the messages in the simulation to that of the messages exchanged with the particular tool under evaluation. He believes that current assessment of

ICT tools for crisis response relies too much on snapshots and static reports, in many cases based on participant or user recollection. By integrating the simulation with the tools, a dynamic dimension could be added to any evaluation efforts to get more in-depth insight about, for example, the specific times of events, the actual locations and point of view of the participants, the delays in between message sending and reception, or the potential inconsistencies that result from disconnected observations. Since the simulation allows message inspection, it could be possible to examine the messages that did not arrive in time or to the right person, indicating the precise context of the origin and destination that would explain such information quality problems. He finished by saying that this would be even more useful if the simulation model could be designed in such a way that the technological tools could be "dragged and dropped" into the simulation environment by non-experts (on simulation).

for ICT assessment,

Regarding the contribution of the simulation to improved understanding of coordination strategies and for enabling discussion of diverging assumptions about coordination (Question 16), he recognized the value in having a simple scenario to focus on the coordination and not on the crisis details. This can help guide discussion about the implications of different coordination strategies, especially when they concern multidisciplinary coordination. Nonetheless, he also believes that a larger set of more detailed crisis environments could help test those insights under different conditions. Specifically, for the PoR, he suggested using an "on water" type of accident, instead of an "on land" type of accident to enable better situated discussions about coordination.

for improved under-standing, and

The last question regarding the use of the simulation model for getting specific insight about the relationship between top-down and bottom-up coordination (Question 17) was answered positively. For him, it is indeed possible to use the simulation for explaining the difference between top-down and bottom-up coordination, but a different issue is whether the insight regarding bottom-up coordination can be carried out in practice. If the insight is aimed at crisis managers trained under a command and control mentality, it "would require some getting used to". Nonetheless, the simulation clearly "sends across the message that during a crisis you cannot do everything on your own" and this holds for first responders, as well as for leaders attempting to coordinate their actions. He also believes that some insight can be obtained regarding the relationship that the scale of the crisis has on increased coordination challenges. While scaling up the response organization is a way of dealing with a larger crisis, the simulation shows that this also creates additional coordination needs.

for gaining insight,

The expert was also given the chance to provide some general comments or final remarks, outside the interview script. He pointed out that while the CoPI team is a standard for all Dutch crisis response, in the PoR it is larger than usual, because it must involve port personnel and environmental management as well. In this sense, the CoPI team can operate in a frustrating manner, spending too much time on "information gathering mode" and less on actual scenario generation and decision making. He firmly believes that ICT can improve this situation and help guide the team out of a reactive state into a proactive state, especially by using collaboration technologies, aided with simulations for scenario generation.

in addition to comments and…

suggestions.

Finally, he suggested that the simulation model could be used to research how to improve situational awareness and information exchange, enabling an exploration of communication failures and their operational impact. In this sense, he agrees that realism should not be emphasized (yet), as it would focus the findings too much on a specific scenario, when it should contribute to understanding the process regardless of the kind of crisis encountered.

Results support the use of the model to gain insight and

Overall, the expert validation shows support for using the simulation model to obtain insight on the aggregate effects of using different coordination mechanisms, in relation to both the size of the incident (specifically attached to the size of the population) and of the response organization (specifically the number of firemen and medics). The agreed upon capability of the simulation to provide an aggregate global view of the crisis in the animation is offset by a tradeoff in terms of the level of detail and dynamics that are displayed. In terms of the experimental results, the evaluation demonstrated their plausibility, especially in terms of the average resulting number of victims. Such results clearly show, in the experts' opinion, the effect of changing coordination mechanisms between the responders, which is the ultimate goal of the simulation model. Moreover, the simulation demonstrates the potential for evaluating the performance and use of specific ICT tools in support of such coordination mechanisms. These capabilities are not only useful in determining the relative performance of different coordination mechanisms, but can also be used in the context of crisis response planning and training by generating useful insight and enabling discussion and revision of current understanding of coordination in crisis response.

provide requirements for new design cycles.

While realism was not an essential aspect of the design, the evaluation provided particular avenues for contributing to added realism in subsequent design cycles. Additional scenarios and environmental objects could contribute such realism and it was the intention behind the simulation architecture that they be developed with relative independence from the agent-based organization. In terms of the responders, additional or more detailed behaviors could be added to the agents, providing more heterogeneity (e.g. preferences, speed, and learning) or indeed more agents (e.g. police, chemical experts, volunteers). Chapter 5 discussed the development process in such a way that additional extensions could follow it in subsequent design cycles. Furthermore, the validation also provides additional information regarding relevant requirements for such future cycles. The simulation model could be adjusted for use a serious game, implying that it could be enabled for user interaction (human-in-the-loop simulation). The simulation model could also be integrated to real ICT tools that are under evaluation (regardless of whether they are currently used or being evaluated for purchase / implementation). This would require not only additional design cycles, but also additional relevance and rigor cycles to specify the requirements together with potential users and determine the best strategy for the architecture to integrate such connectivity in a component-based approach (cf. Verbraeck & Valentin, 2008). Finally, it should be noted that when conducting expert face validation of agent-based models, agreement or disagreement should not be used to determine correctness, but rather the model can be used for testing, guiding and refining diverging assumptions (Louie & Carley, 2008).

6.3 Metamodeling

With a verified and validated simulation model, the simulation method proceeds with metamodeling as a way to generate an abstract and formal representation of the most meaningful factors and interactions which embodies the insight that can be obtained with the simulation model in terms of alternative coordination mechanisms for crisis response. The metamodel not only contains the essence of the simulation model with respect to specific research questions, but also enables its use as a proxy for the simulation model, enabling a faster, simplified way of running experiments. Since different metamodels can be obtained for the same simulation, a clear definition of the goals and domain of applicability need to be considered, together with the determination of the measure that will be used to evaluate the fit of the metamodel with respect to the simulation.

The experimental design that follows is a systematic way of preparing experiments with the simulation model in order to enable obtaining a regression metamodel. A *metamodel* (or *response surface*, *auxiliary model*, *emulator*, etc.) is a model or approximation of the implicit Input/Output (I/O) function that characterizes the relationship between inputs and outputs in much simpler terms than the full simulation model and can contribute to understanding the problem situation and conducting what-if studies (Kleijnen, Sanchez, Lucas, & Cioppa, 2005). Metamodeling through design of experiments (DOE) is especially beneficial when there is lack of sufficient real data for comparison (Kleijnen, 1999a, 1999b). In addition, it is increasingly used for analyzing agent-based simulations (Kleijnen *et al.*, 2005; Sanchez & Lucas, 2002). First, we must identify the factors and their characteristics, along with the domain of applicability (or experimental region) that determines the combination of values for which the metamodel will be valid (*ibid.*). Potential factors are grouped into five categories: incident, civilian, responder, infrastructure and coordination factors.

Metamodeling through design of experiments …

Incident factors: These factors determine the configuration of the incident in crisis response simulations (*cf.* Chen & Decker, 2005; Comfort, Ko *et al.*, 2004). In our case, the initial crash location, the initial fire size, and the time of the explosion can be set. The crash location cannot be determined directly since it depends on the location of the vehicles that crash (the truck and the excavator) so it will not be explicitly considered. Because we are aiming at an analysis which holds for the same incident, the initial fire size and time of explosion are fixed.

starts with potential factors for the incident,

Civilian factors: These factors determine the initial configuration of civilians (their number, location and life function) and are used in crisis response simulations that include victim rescue (cf. Chen & Decker, 2005). The starting number of civilians is expected to have an effect on the response outcome so a low and high value will be used. The initial location of each civilian will depend on a pseudorandom distribution of civilians inside the incident area, which will affect the population density close to the fire and result in different likelihood of victims. The life function will remain fixed as a way to determine how the civilian becomes a victim and how the victim becomes a fatality, based on contact with the fire and on increased severity if no assistance is given after some time.

for the civilians,

Responder factors: these factors establish the configuration of responders per discipline (their starting number, their starting location, and their speed). Since responders and their coordination are the object of study, such factors are often used in crisis response simulations (cf. Delgado, Pujol, & Sangüesa, 2003; Excelente-Toledo & Jennings, 2003; Massaguer *et al.*, 2006). The starting number of responders should have an effect contrary to the number of civilians. As with the civilians, the initial number of responders will be varied between a low and high value. The starting location of the civilians will be fixed at the location of their station, meaning that this factor will depend on the location of the corresponding *House* (see Chapter 5) and will not be determined as part of the responders factors. Although in reality responders might come from different locations, we want to avoid any advantage that could follow from pre-existing closeness to the incident, giving all responders from each discipline equal initial conditions. Similarly, though individual responders can have different speeds, the speed will be kept constant for firemen and medics, although slightly faster for the firemen, corresponding to the real-life expectation for the firemen to be the first on site (this is a binding requirement for fire services in The Netherlands). Moreover, despite the fixed "constant" speed, responder movements will be handled by an *AnimatedObject* (see Chapter 5) which uses the speed constant as basis for linear interpolations that follow a normal distribution, so in the simulation individual responders will in fact have different speeds that depend on fixed mean and standard deviations for the movement distribution.

for the responders,

Infrastructure factors: This final set of factors determines the initial number and location of infrastructure elements, simplified in terms of houses and vehicles (cf. Massaguer *et al.*, 2006; Xu, Liao *et al.*, 2006). Again, since we want to focus on different organizational and coordination configurations, infrastructure factors will remain fixed. All houses will be given a location in the incident area and two of those will represent the fire station and hospital from where the firemen and medics will be deployed respectively. Vehicle locations will be determined in advance so that once the simulation starts, the vehicles will start moving and the ensuing collision between the truck and the excavator will end up occurring somewhere near the center of the simulated area to make visualization more focused. The distance of the fire station and hospital from the crash location is determined so that the firemen will arrive approximately 10 minutes after receiving the alarm (once again, corresponding to real world expectations).

for the infra-structure,

Coordination factors. Since the main goal of the simulation study is to compare coordination mechanisms, specifically hierarchically mediated coordination to autonomous mutual adjustment, the key factors related to coordination within and between disciplines are rescue and assignment. Both factors will express the possibility of having two different coordination mechanisms for the same coordination dependency, in keeping with the information-processing terminology. An interdisciplinary rescue dependency will operationalize a fit dependency where two activities (rescue by medic or rescue by firemen) should produce a single outcome (assistance of a victim). Coordination of this dependency can be achieved either through mediation of a shared data space (see Chapter 5) or through mutual adjustment by observing each others' actions. In this case when two or more responders "target" the same victim, all but the first will change their choice upon observing that the victim has already been assisted.

and for the coordination mechanisms.

The second coordination dependency is an intradisciplinary resource sharing dependency, where a single resource (fireman), must be shared between two activities (fight fire or rescue). It can be managed by two alternative coordination mechanisms. Mediated (hierarchical) coordination is achieved when assignment is decided by the Fire Officer. Alternatively, assignment is done autonomously by each fireman cyclically. After completing one rescue or one fire fighting cycle (see Fireman behavior in Appendix B), the decision is revised, but still autonomous and will depend on the local observations of each fireman, rather than on a general containment plan determined by the Fire Officer after Consultation with the Medical Officer (see OvD and OvD-G behaviors in Appendix B).

Potential factors may be included in the experimental design or fixed at nominal (or base) levels a priori (Kleijnen *et al.*, 2005). In Table 6-3 all potential factors are identified next to the corresponding decision to include them or not.

Table 6-3 Potential factors

Factor		Description	Included or Excluded?
Incident	IF	Initial fire size	Excluded. Set at 4 X 4.
	TE	Time of explosion	Excluded. Set at 15 minutes after crash to comply with the original crisis scenario description (Vignette in Chapter 1) prompting a call for backup firemen.
Civilians	C	Number of civilians	Included. Should influence the number of victims.
	LF	Life function	Excluded. Increases victim severity upon contact with the fire or becomes fatality if not rescued after one hour.
	CL	Location of civilians	Excluded. Pseudorandom distribution, avoiding placement where the vehicles move.
Responders	F	Number of firemen	Included. It is expected that a high number of firemen will improve response efforts.
	M	Number of medics	Included. More medics should improve the response efforts.
	FS	Firemen Speed	Excluded. Pseudorandom numbers are used in a linear interpolation that determines movement using a normal distribution.
	MS	Medics Speed	Excluded. As in Firemen Speed but slightly slower.
Infrastructure	HL	Location of houses	Excluded. Spaced evenly avoiding the space that the vehicles use to move. Fire station located at (-80, 80) and Hospital located at (10, 80), where the center of the simulation area is (0, 0).
	VL	Location of vehicles	Excluded. Spaced evenly around starting position (on the same Y-coordinate) so that crash occurs near (0, 0).
	VS	Vehicle speed	Excluded. As in Firemen Speed but faster.
Coordination	R	Rescue coordination	Included. Operationalizes rescue coordination mechanism as choice between mediation and mutual adjustment.
	A	Assignment coordination	Included. Operationalizes assignment of firemen as a mediated or autonomous coordination mechanism.

Five factors are selected.

Out of the initial potential factors, five are selected for inclusion in the experimental design using specific factor levels. The result constitutes the domain of applicability, or experimental region for which the metamodel will be valid (Kleijnen & Sargent, 2000). Such domain of applicability is shown in Table 6-4, indicating two levels for each factor and two qualitative factors, which is common practice in DOE (Kleijnen, 1999b).

Table 6-4 Domain of applicability (factors and factor levels)

Factor	Description	Factor levels
C	Number of civilians (interval scale)	Low (50) / High (100). Factor levels are obtained from the accident sizes and proportions found in Appendix A (Table A-4. Accident with flammable explosive substance). A small accident size of the kind simulated (I-II in Table A-4) should result in an average maximum number of fatalities of 5 ("# of dead victims" in Table A-4) and a number of victims to rescue of between 5 and 15. After some exploratory runs, 50 civilians came close to an average 2 fatalities, and for 100 civilians, close to 5 fatalities. The "# of people to rescue" corresponds to the victims (V) in our simulation which ranged between 4 and 13 on the same exploratory runs of 50 and 100 C, respectively.
F	Number of firemen (interval scale)	Low (10) / High (20). Factor levels are determined in proportion to the number of victims in the incident area (one team, according to Table A-4). However, in order to comply with the original scenario description, a second team is included in the form of a backup group alarmed after the explosion. Thus, the low and high numbers are divided equally into the first response and the backup team (5 or 10 each).
M	Number of medics (interval scale)	Low (5) / High (10). Factor levels are determined again following the guidelines from Table A-4 regarding the minimum number of victims to rescue (5) as low level for the corresponding medical unit. In this case, there is no backup team, since the backup is meant to reinforce fire fighting, not victim rescue, which is already a shared responsibility between medics and firemen.
R	Rescue coordination (nominal /categorical)	Mediated (0)/ Autonomous (1). Categorical value coded at two levels to allow regression analysis of a qualitative variable through a "dummy" binary variable (Allen, 1997, p. 128; Kleijnen & Sargent, 2000).
A	Assignment coordination (nominal /categorical)	Mediated (0) / Autonomous (1). Categorical value coded at two levels to allow regression analysis of a qualitative variable.

Besides the factors, DOE continues by identifying the output variables, which in DOE are called *responses (Kleijnen et al., 2005)*. Responses are classified into two categories: response effectiveness and coordination cost.

Outputs are related to…

Response effectiveness: The effectiveness of the response is determined by how long the overall response takes and how many victims are rescued. Response time can be seen as the most critical measurement of performance in crisis response (cf. Chen & Decker, 2005). Since one of the main goals of crisis response is protecting human life (Suárez *et al.*, 2005), the resulting number of victims will be determined as an additional effectiveness measure. This variable determines in the end how many (or what percentage) of the people involved end up counting as victims. It is further decomposed according to severity, counting the fatalities as a separate response which constitutes a subset of the number of victims.

response effectiveness and

Coordination cost: The effectiveness of coordination can be measured through coordination cost as a comparative variable. The volume of messages exchanged between the agents can be used to measure coordination cost (Xu, Scerri, Sycara, & Lewis, 2006). The assumption is that in multi-agent systems "coordination is achieved through communication by message passing." (Chaudhury, Deng, & Rathnam, 1996). This response can be further decomposed into messages exchanged within the disciplines (counted separately for the fire and medical services) and between the disciplines (counted as interdisciplinary messages). For details on the counting of messages see the Vignette in the end of Chapter 5.

coordination cost.

An overview of the responses is shown in Table 6-5.

Table 6-5 Response variables

Response		Description
Response effectiveness	RT	Response Time (interval scale): measures the time (in minutes) in between the start of the vehicle movement and the return of the responders to their original locations.
	NV	Resulting number of victims (interval scale). Counts the number of civilians affected by the fire, regardless of whether they are rescued or not. NV <= C.
	NF	Resulting number of fatalities (interval scale). Subset of NV with highest severity. Only rescue can prevent fatalities, since the life function assumes that time (or repeated contact with the fire) always increases severity and only assistance can decrease it. NF <= NV.
Coordination cost	FM	Number of messages exchanged between agents inside the fire discipline (interval scale).
	MM	Number of messages exchanged between agents inside the medical discipline (interval scale).
	IM	Number of interdisciplinary messages exchanged across agents of fire and medical services (interval scale).
	CC	Total coordination cost as determined by the total number of messages exchanged between the agents (interval scale). CC= FM + MM + IM.

Before the actual experimental design, the kind of metamodel and its expected accuracy and validity measures should be specified (Kleijnen & Sargent, 2000). Given our goals of gaining insight or improved understanding, enabling comparison, and contributing to validation, we are interested on the main effects and two-way interaction effects of the factors on the responses (*ibid.*). As a result, a first-order polynomial regression model augmented with interaction effects between pairs of factors can be obtained. Such a polynomial model is a good compromise between simple first-order polynomials which miss interaction effects and higher order polynomials which are harder to interpret and need many more simulation runs (Kleijnen, 1999b). Since our goal is not optimization, calibration or prediction, we will be mainly interested in the direction and magnitude of the effects on individual responses, not on the actual values.

A polynomial regression model can be obtained...

The metamodel is specified as an additive polynomial:

(Equation 1)

$$y = \beta_0 + \sum_{h=1}^{k} \beta_h x_h + \sum_{h=1}^{k} \sum_{h<i}^{k} \beta_{hi} x_h x_i + \varepsilon$$

where y is the simulation response, x_i denotes the value for factor i, and k is the number of factors. The intercept is β_0; β_h is the main effect of factor h; and β_{hi} are the two-factor interaction effects between factors h and i. Using Ordinary Least Squares (OLS), the metamodel will be fitted to data from the simulation experiments; the resulting fit will be evaluated by the R^2 value, or coefficient of determination (Kleijnen & Sargent, 2000), which we will label as R^2 (in italics) to distinguish it from our R factor. The above equation assumes one single response, so y will correspond to RT, NF and CC, resulting in three separate metamodels.

In order to design the experiments, there is a wide array of alternative designs, depending on the number of factors and the complexity of the response surface. These include: (fractional) factorial designs, sequential bifurcation, central composite designs, fine grid and Latin hypercube designs (Kleijnen *et al.*, 2005). Our domain of applicability has identified five factors, each with two possible factor levels. As a result we are able to use a full factorial design to obtain the experimental results needed for a first-order polynomial regression model with two-way interaction effects. Using a gridded or factorial design, where 2^k design is the simplest (each factor taking on two possible values, as in our case) and m^k is the general form, we obtain a full factorial design of 32 scenarios (design points or treatments), seen in Table 6-6.

through a full factorial experimental design.

Table 6-6 Design matrix for the 2^n (n=5) full factorial design

Scenario	C	F	M	R	A
1	50	10	5	1 (Autonomous)	1 (Autonomous)
2	50	10	5	1 (Autonomous)	0 (Mediated)
3	50	10	5	0 (Mediated)	1 (Autonomous)
4	50	10	5	0 (Mediated)	0 (Mediated)
5	50	10	10	1 (Autonomous)	1 (Autonomous)
6	50	10	10	1 (Autonomous)	0 (Mediated)
7	50	10	10	0 (Mediated)	1 (Autonomous)
8	50	10	10	0 (Mediated)	0 (Mediated)
9	50	20	5	1 (Autonomous)	1 (Autonomous)
10	50	20	5	1 (Autonomous)	0 (Mediated)
11	50	20	5	0 (Mediated)	1 (Autonomous)
12	50	20	5	0 (Mediated)	0 (Mediated)
13	50	20	10	1 (Autonomous)	1 (Autonomous)
14	50	20	10	1 (Autonomous)	0 (Mediated)
15	50	20	10	0 (Mediated)	1 (Autonomous)
16	50	20	10	0 (Mediated)	0 (Mediated)
17	100	10	5	1 (Autonomous)	1 (Autonomous)
18	100	10	5	1 (Autonomous)	0 (Mediated)
19	100	10	5	0 (Mediated)	1 (Autonomous)
20	100	10	5	0 (Mediated)	0 (Mediated)
21	100	10	10	1 (Autonomous)	1 (Autonomous)
22	100	10	10	1 (Autonomous)	0 (Mediated)
23	100	10	10	0 (Mediated)	1 (Autonomous)
24	100	10	10	0 (Mediated)	0 (Mediated)
25	100	20	5	1 (Autonomous)	1 (Autonomous)
26	100	20	5	1 (Autonomous)	0 (Mediated)
27	100	20	5	0 (Mediated)	1 (Autonomous)
28	100	20	5	0 (Mediated)	0 (Mediated)
29	100	20	10	1 (Autonomous)	1 (Autonomous)
30	100	20	10	1 (Autonomous)	0 (Mediated)
31	100	20	10	0 (Mediated)	1 (Autonomous)
32	100	20	10	0 (Mediated)	0 (Mediated)

Besides the strategic design of the experiments, it is also required to determine the tactical issues of number of replications (runs, observations) and variance reduction techniques (e.g. common pseudorandom numbers, or CRN) (Kleijnen & Sargent, 2000). In our case, 10 replications were run for each scenario; per the recommended minimum desirable number of replications for simulation experiments (Banks *et al.*, 1999, p. 448). Moreover, the reduction in standard deviation for response time was checked and showed that while there was a slight improvement when adding more replications, it was insufficiently significant to increase the number of replications, considering that each one takes on average 5 minutes of real time. To illustrate, the mean response time with 5 replications of the 32 scenarios is 137 minutes with standard deviation of 34; for 10 replications, the mean is 136.9 and the standard deviation is 33.4. Each replication uses a different seed for generating a stream of pseudorandom numbers – for details on how these numbers are generated, see the D-SOL simulation suite (Jacobs, 2005, pp. 88-90). Although using the same set of ten seeds would enable overlapping streams of pseudorandom numbers for reducing variance and sharpening comparisons, using common pseudorandom numbers violates the assumption of having independently identically distributed (IID) outputs, as assumed by most statistical methods (Kleijnen *et al.*, 2005). Accordingly, the seeds are not the same between scenarios.

Graphical analysis of experimental results

Results are analyzed with scatter plots…

To analyze the results of the experiments we use graphical analysis tools that can provide evidence of structure and interesting cases. The first is a scatter plot of the individual and mean values for response time, coordination cost and number of victims, shown in Figure 6-1.

The individual values for each scenario correspond to each of the ten replications and the mean is the average for those ten replications. On the X-axis we find each of the 32 scenarios. This axis does not represent a scaled variable; rather, it labels each scenario as a category variable corresponding to the scenario number in Table 6-6 – as in the table, the scenarios are divided into eight groups of four indicating the different coordination setups (autonomous-autonomous, autonomous-mediated, mediated-autonomous, and mediated-mediated).

To ease reading of the plots, the eight groups are labeled with a lower case for each low level factor, and an upper case for each high level factor, as follows: ‘cfm’ represents Scenarios 1-4, indicating low levels of C, F and M; cfM represents Scenarios 5-8, indicating low levels of C and F, but a high level in M. Similarly, the rest of the labels are: cFm (Scenarios 9-12), cFM (scenarios 13-16), Cfm (Scenarios 17-20), CfM (Scenarios 21-24), CFm (Scenarios 25-28), and CFM (Scenarios 29-32).

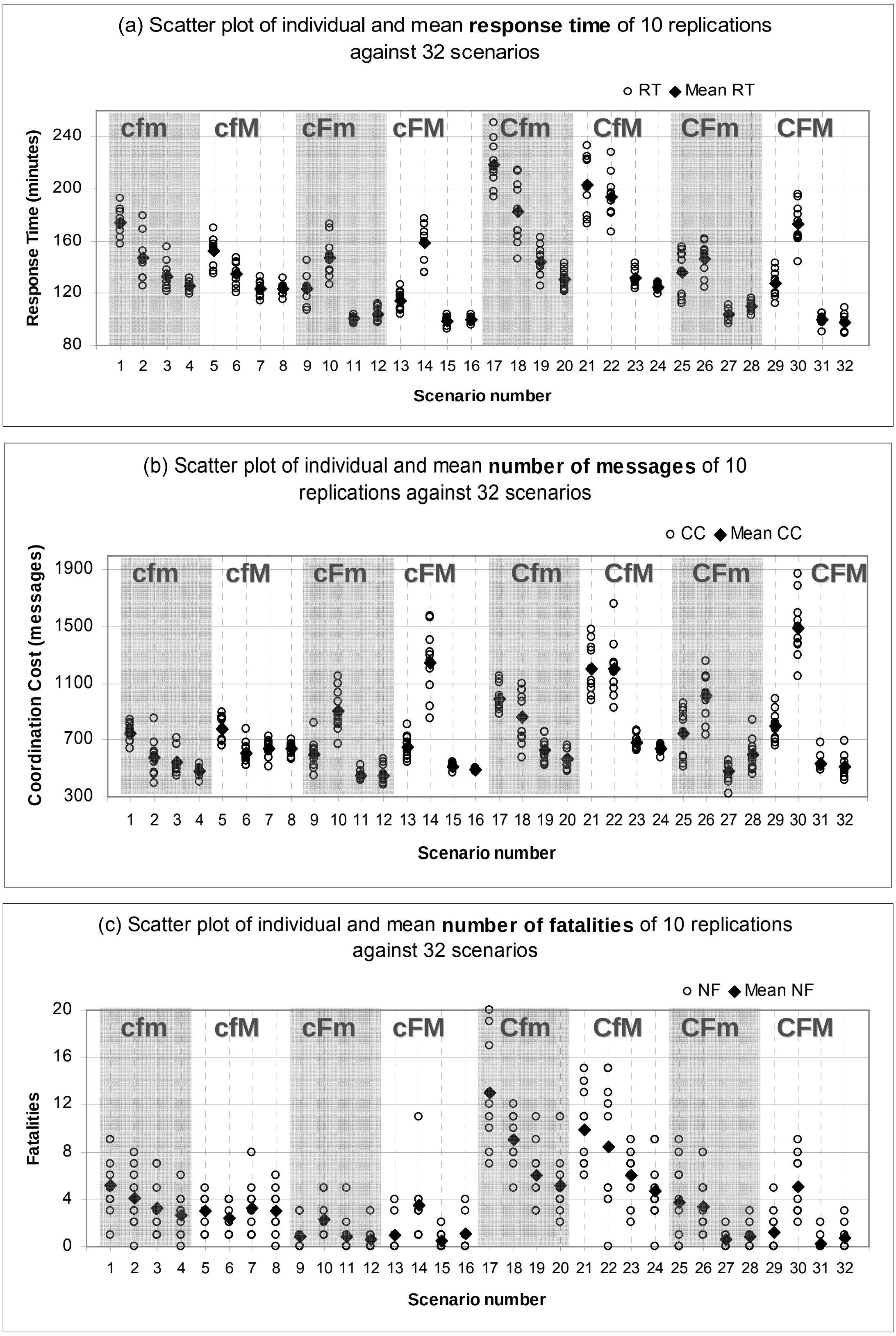


Figure 6-1 Scatter plots of response time, messages and fatalities

showing evidence of structure…

The scatter plot in Figure 6-1.a show some evidence of structure in the data. Half of the scenarios (cfm, cfM, Cfm, and CfM) show an increasingly faster response going from the first to the last (4, 8, 20, 24) scenario in each group. For the other half (cFm, cFM, CFm, and CFM), the second scenario in each group (10, 14, 26, 30) is the slowest on average, while the fastest scenarios are split between the third and the fourth. This last result shows that mediated rescue and autonomous assignment can perform slightly better than the all-mediated scenario.

and interesting cases…

Unsurprisingly, there is a connection between response time and coordination cost, shown as total number of messages on Figure 6-1.b. In both cases the structure of the responses for all 32 scenarios follows a similar pattern. Scenarios 14 and 30, which already showed poor performance in terms of response time, also appear with a significantly higher coordination cost, as compared to their group (cFM and CFM, respectively). What these scenarios have in common is the largest possible number of responders coordinating rescue autonomously and using mediated assignment of firemen. This suggests the worse configuration of coordination mechanisms for a large number of responders.

for further experiments.

The third scatter plot (Figure 6-1.c) shows the individual and mean number of fatalities. As the initial location of the civilians is pseudorandom, the data points have larger scattering than RT or CC for most scenarios, when compared to the other two responses. Nonetheless, the mean values still show a similar structure. The overall evidence of the figure can be summed up by looking at Scenario 17 which shows in a nutshell that the worse performance comes with a high number of civilians and a low number of responders using autonomous coordination. In addition, Scenario 14 shows an apparent outlier, indicating once again an interesting case for further experiments.

Using mean plots…

By considering all graphs together, going from scenario 1 to 16 (lower case 'c') and from 17 to 32 (upper case 'C') shows the effect of increasing the number of responders; this is more evident for a larger initial number of civilians (17 to 32, labeled with upper case 'C'). In order to get more information about the relative importance of the factors, we continue with our second graphical analysis using mean plots which simplify the aggregate effect of each of the five factors on the main responses on average.

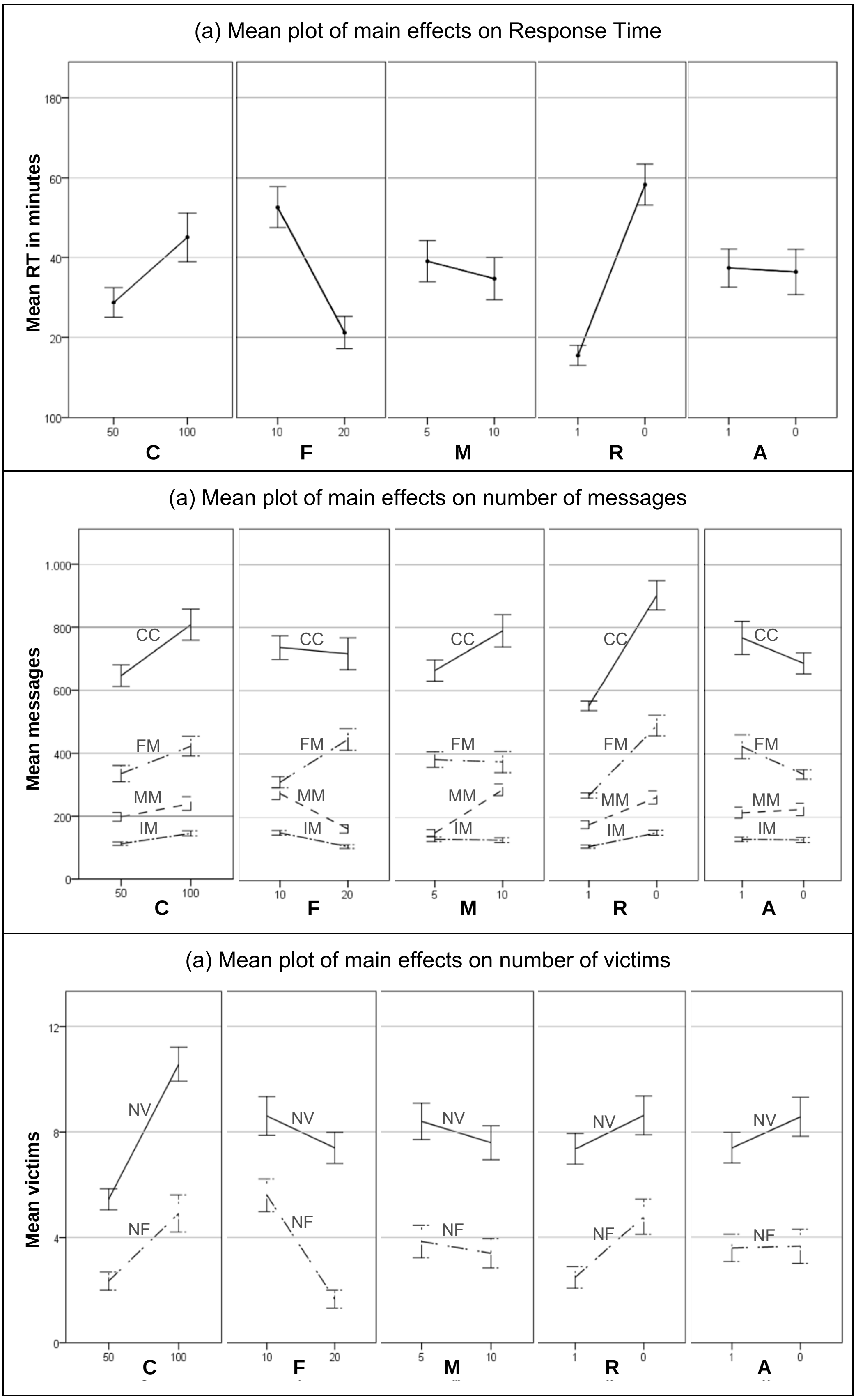


Figure 6-2 Mean plots of main effects (95% confidence interval)

Figure 6-2 shows the mean plots of main effects on (a) response time, (b) coordination cost, and (c) victims and fatalities. En each case, the low and high values of the factors are averaged over their corresponding half of the scenarios (16 scenarios or 160 replications). From Figure 6-2 it is clear that increasing the initial number of civilians will increase all response factors. Conversely, increasing the number of firemen results in a reduction of the response outputs, except of course for FM (number of messages exchanged within the fire discipline) and less significantly for CC (total coordination cost) in Figure 6-2.b. With respect to the medics, the improvement of response effectiveness can be seen but is less pronounced than with the firemen. In addition, from Figure 6-2.b and akin to the number of firemen, more medics imply more messages exchanged within the medical discipline (MM). However, as opposed to the firemen, more medics will actually increase total coordination cost (CC). This, together with the slight improvement in response time and number of victims and fatalities, shows agreement with the results from the expert validation, where there was not enough strong support for the main effects caused by the number of medics.

illustrates the main effects.

In terms of rescue coordination (R), it is apparent from the figures that mediated rescue is significantly better than autonomous rescue. On the other hand, with respect to assignment coordination (A), there is no significant improvement in response time (RT) or in number of fatalities (NF) when using mediation. In addition, while mediated coordination (whether of rescue or assignment) would be expected to increase coordination cost, this is only true of assignment. The fact that mediated rescue actually decreases coordination cost is due to the fact that the response is much faster reducing the amount of time spent on all response activities including coordination).

Looking at the effects on the number of victims and fatalities (Figure 6-2.c) it can be seen that there is more impact on fatalities than on victims, particularly in terms of the number of firemen and the rescue coordination. This shows that the number of victims is closely related to the initial number of civilians and that it is unlikely for any configuration to reduce this number further, given that it will always take time for the rescuers to arrive. On the other hand, preventing fatalities can be subject of major improvements.

Regression metamodel analysis

In order to derive statistical conclusions about factor effects, the linear regression metamodel defined in *Equation 1* (earlier in this section) is applied. Since each scenario is replicated ten times, altogether 320 data points enter the regression analysis. Since we are using two categorical dummy binary variables, it should be noted that "a regression model can include both continuous and categorical independent variables at the same time. This procedure is known as analysis of covariance" (Allen, 1997, p. 147). This does not preclude the use of OLS for obtaining the metamodel. However, special care is needed so that one of the categories of the dummy variables is excluded to avoid multicollinearity. The assignment (A) and rescue (R) factors include just one category in each case (that of being autonomous, where mediation is kept as the base category). We will produce two separate metamodels for each of the responses. One for the main

Regression analysis proceeds…

effects (Equation 1 without interaction effects) and one extended with interaction effects (Equation 1). The resulting metamodels are specified in Table 6-7.

Table 6-7 Metamodel specifications

Metamodel	Specification
Main effects on RT	$RT_1 = \beta_0 + \beta_C C + \beta_F F + \beta_M M + \beta_R R + \beta_A A$
RT_1 augmented with interaction effects	$RT_2 = \beta_0 + \beta_C C + \beta_F F + \beta_M M + \beta_R R + \beta_A A$ $+ \beta_{CF} C^*F + \beta_{CM} C^*M + \beta_{CR} C^*A + \beta_{CR} C^*R + \beta_{CF} C^*A$ $+ \beta_{MF} M^*F + \beta_{FR} F^*R + \beta_{FA} F^*A + \beta_{MR} M^*R + \beta_{MA} M^*A$
Main effects on NF	$NF_1 = \beta_0 + \beta_C C + \beta_F F + \beta_M M + \beta_R R + \beta_A A$
NF_1 augmented with interaction effects	$NF_2 = \beta_0 + \beta_C C + \beta_F F + \beta_M M + \beta_R R + \beta_A A$ $+ \beta_{CF} C^*F + \beta_{CM} C^*M + \beta_{CR} C^*A + \beta_{CR} C^*R + \beta_{CF} C^*A$ $+ \beta_{MF} M^*F + \beta_{FR} F^*R + \beta_{FA} F^*A + \beta_{MR} M^*R + \beta_{MA} M^*A$
Main effects on CC	$CC_1 = \beta_0 + \beta_C C + \beta_F F + \beta_M M + \beta_R R + \beta_A A$
CC_1 augmented with interaction effects	$CC_2 = \beta_0 + \beta_C C + \beta_F F + \beta_M M + \beta_R R + \beta_A A$ $+ \beta_{CF} C^*F + \beta_{CM} C^*M + \beta_{CR} C^*A + \beta_{CR} C^*R + \beta_{CF} C^*A$ $+ \beta_{MF} M^*F + \beta_{FR} F^*R + \beta_{FA} F^*A + \beta_{MR} M^*R + \beta_{MA} M^*A$

In regression analysis it is often the case that inclusion of factors and their interactions should be decided upon based on theoretical assumptions (Allen, 1997, p. 121). In our case, metamodeling is used as a way to perform an exploratory analysis of the factor effects and interactions to obtain new theoretical insight. In such cases, regression is usually performed in a stepwise manner to screen for significant factors (Cohen, 1991; Storlie & Helton, 2008). In a stepwise regression the most influential variable is added to the model first; then the next most influential variable is added to the model and the process is continued in this manner until no more influential variables can be identified (Storlie & Helton, 2008). However, such forward selection method can produce misleading results when using certain categorical dummy variables and this problem can be avoided using backwards selection (Cohen, 1991).

using a stepwise method…

Using a backwards selection method with the SPSS/PASW 18 software will enter all variables into the model and the weakest (less significant) variable will then be removed and the regression recalculated; if the restricted model is weaker (according to an F-test using .05 significance level), the variable will be re-entered; otherwise, the variable will be removed and the process repeated until only significant factors remain.

with backwards selection…

first testing for construct significance of the…

The first metamodel for each response (RT_1, NF_1 and CC_1) is meant to address the main effects of the factors without interaction effects. But two of those factors (A and R) are categorical dummy variables so determining their significance should avoid the problem of rejecting a significant construct (e.g. assignment coordination) just because one of the categories (e.g. autonomous assignment, coded with the A factor) is not significant. Although this is more of a potential problem when using dummy variables for constructs of more than two categories, it can still be avoided by testing the model with all categories (Polissar & Diehr, 1982). Accordingly, for generating the main effects models we will use the backwards selection method with the original factors, as well as using the opposite base category (mediation), which in practice means inverting the values of A and R so that mediation= 1 and autonomy = 0.

categorical variables.

The best fitting main effects models will then indicate whether the constructs as a whole are significant for that particular response. The factors selected in this first screening are the ones that will be included in the subsequent backward selection including interaction effects. By removing insignificant categorical constructs from the main effects model we avoid including interaction effects with any of those categories but without the original dummy variable itself, which would render those interactions meaningless. For example, if A is removed from a main effects model, it will not be possible for it to act as moderator on F, resulting in a metamodel that includes A*R but not A (which would be meaningless). It should be noted that the selected model will come from the use of the original coding of A and R and the alternate coding will only be used for confirmation. The subsequent models for interaction effects will also use the original coding of A and R (mediation as base category) and not the alternate version.

The resulting metamodels specify:

The full set of alternative main effects models generated for RT can be found in Appendix D. The selected RT_1 can be seen in Table 6-8.

Table 6-8 Main effects model for response time (RT)

Model		Coefficient	Std. Error
RT_1	(Constant)	144	5.6
R^2= 0.697	C	0.33	0.04
	F	-3.1	0.2
	M	-0.88	0.4
	R	43	2

the main effects on response time …

The resulting metamodel has an R^2 of 0.697, which accounts for nearly 70% of variation in the data. Of all possible factors, Table 6-8 shows that using a backwards stepping method for the regression analysis, the best fit is obtained with all factors except for A, which is confirmed by using the alternate coding for A and R, making the construct insignificant for RT. This indicates what the graphical results had already shown: there is no significant main effect on response time that depends on coordination assignment. What we are able to say now using the coefficients is the average amount that RT increases when the included factors (C, F, and M) are increased one unit and other factors are held constant. The effect of an additional fireman (F) is to reduce response time (RT) in 3.1 minutes. Conversely, the effect of an additional civilian (C) is to increase RT by 0.33 minutes. While the effect of an additional medic (M) can be predicted by the model to reduce RT in 0.88 minutes, the relatively high standard error should also be considered, indicating that the improvement is slight, which confirms the graphical analysis regarding the main effect of medics.

Because R is a binary variable, the coefficient is the amount that response time increases when R=1 (again, R=0 if autonomous or R=1 if mediated) compared to the reference category (mediated rescue which is not included as a dummy variable to prevent multicollinearity). Thus, the effect of autonomous rescue, instead of mediated rescue is to increase response time by 43 minutes.

The model can now be extended to include interaction effects between the variables. Once more, a backwards method will be used to include the most significant factors only. The complete set of metamodels at each step can be seen in Appendix D, while the selected metamodel RT_2 is shown in Table 6-9.

augmented with interact-tion effects;

Table 6-9 Main effects model for response time (RT) augmented with interaction effects

Model		Coefficient	Std. Error
RT_2	(Constant)	132	13.6
R^2= 0.762	C	0.72	0.12
	F	-0.87	0.83
	M	-3.84	1.23
	R	10.2	9.79
	C*F	-0.04	0.007
	C*R	0.48	0.07
	M*F	0.17	0.07
	F*R	-0.71	0.37
	M*R	0.95	0.74

RT_2 shows a better fit with respect to RT_1 accounting for 6.5% more of the variability in RT. However, it should be noted that because of the inclusion of R, the factors F, FR, and MR are also included despite having a significance higher than 0.05 for the t-test. The effects of autonomous rescue should include the aggregate effect of the interactions. Thus, for autonomous rescue there is an increase in RT of 0.48 minutes for each additional civilian (the most significant interaction is C*R). An additional effect (with a higher standard error) increases RT by 0.95 minutes for each additional medic (M*R), i.e. autonomous rescue makes the medics ineffective. Another effect on RT with high standard error reduces it by 0.71 minutes for each additional fireman (F*R), i.e. while autonomous rescue has a negative effect, it is not enough to make the firemen ineffective, just less effective than when using mediated rescue.

In addition to the effect of rescue coordination, RT increases, as expected with a higher number of civilians (C) resulting in an additional 0.72 minutes for each civilian and an additional 0.48 minutes when rescue is autonomous (C*R). Conversely, each additional fireman (F) reduces RT by 0.87 minutes and an additional 0.71 when rescue is autonomous (F*R). The effect of additional medics (M), while positive in terms of RT (negative sign) is offset by the interaction with autonomous rescue (M*R), which makes the rescue efforts slower, and by the interaction with firemen (M*F) because some subset of them might actually take on the role of medics, decreasing the aggregate contribution of the medical discipline to RT. The aggregate effect then becomes a reduction in 2.7 minutes for each additional medic. This multiple interaction effects suggest the reason why the graphical analysis could not account for the main effect of medics.

the main effects on fatalities …

The next metamodel is related to the main effects on the number of fatalities (NF_1), which is the other output related to crisis response effectiveness that we are interested in. The resulting models generated by the backwards stepping method are contained in Appendix D. The selected metamodel, confirmed by the regression using the alternate coding for A and R, is shown in Table 6-10.

Table 6-10 Main effects model for number of fatalities (NF)

Model		**Coefficient**	**Std. Error**
NF_1	(Constant)	4.54	0.67
$R^2 = 0.492$	F	-0.4	0.03
	C	0.05	0.006
	R	2.3	0.3

The resulting metamodel has an R^2 value of 0.492 indicating that it can account for almost 50% of the variability in NF. The other half is still an effect of the number of victims, which depends on the initial "geographical" distribution of civilians in the crisis environment. While this makes the metamodel fit the data only partially, it also serves as a reminder that certain conditions during a crisis are simply outside of the control of the response organization and even if it is possible to plan and train for an estimated number of civilians, it will not be possible to predict their exact location in reality.

In any case, reducing the number of fatalities will be possible mainly by adding additional firemen: 0.4 less fatalities on average for each one. The coefficient for C, indicates that each additional civilian will on average result in 0.05 fatalities. Finally, R is seen to have a negative effect in the number of fatalities, resulting in an increase of 2.3 when using autonomous rescue. The absence of autonomous assignment or medics from the model indicates their insignificant effect on NF which had already been apparent from the graphical analysis.

augmented with interact-tion effects;

However, because medics already showed interaction effects with respect to RT, we will still include M to generate metamodel alternatives with interaction effects. The models obtained with a stepwise backward method are contained in Appendix D and the selected NF_2 (including M) is specified in Table 6-11.

Table 6-11 Main effects model for number of fatalities (NF) augmented with interaction effects

Model		Coefficient	Std. Error
NF_2	(Constant)	-1.3	2.3
R^2= 0.608	C	0.15	0.02
	F	0.1	0.1
	M	-0.18	0.24
	R	0.2	1.4
	C*F	-0.008	0.001
	C*M	-0.001	0.002
	C*R	0.06	0.01
	M*F	0.02	0.01
	F*R	-0.08	0.05
	M*R	-0.14	0.1

The augmented metamodel for NF shows an improvement of fit with respect to NF_1, accounting for an additional 11.6% in variability, according to the R^2 value. The main influencing factor on fatalities is once again the use of autonomous rescue (R) which increases NF by 0.2, plus the additional effect through moderation (C*R, F*R, M*R), which shows that it is only offset by increasing the number of firemen and medics (both interactions have a negative sign).

Besides the effect of rescue coordination, and as expected, for each civilian (C) there is an increase of 0.15 fatalities on average which is offset by each additional fireman and medic, considering their interactions (F, M, C*F, C*M, M*F, F*R, M*R). In this respect, it should be noted that the aggregate of firemen (adding all coefficients for firemen and its interaction effects) is of increasing the number of fatalities (0.1 – 0.008 + 0.02 -0.08) when rescue is autonomous. Through the animations, it is possible to see that this is the effect of redundancy. The fact that each fireman autonomously decides the victim to rescue and that all fireman are originally in the same position means that in many cases they will select the same victim and even after mutually adjusting their behavior they will change their choice once more without consultation repeating the effect of redundancy and rendering the effect of additional rescuers virtually superfluous.

In effect, this means that when the firemen take on the role of medics they will have the same negative effect when using autonomous rescue and their positive influence will only be apparent in a reduction of response time. Nonetheless, when rescue is mediated, additional firemen will indeed reduce the number of fatalities significantly, as can be seen in Figure 6-2.c.

and the main effects on coordination cost…

Besides response effectiveness, we also want to see the effect that different coordination mechanisms have on coordination cost as measured by the number of messages. Considering only the main effects we can obtain a metamodel for CC using a backwards stepping method. The complete set of metamodels can be found in Appendix D, while the selected one is specified in Table 6-12 and the resulting factors are confirmed by the analysis using the alternate coding for the dummy variables (A and R).

Table 6-12 Main effects model for coordination cost (CC)

Model		Coefficient	Std. Error
CC_1	(Constant)	160.7	49.7
$R^2 = 0.536$	R	350.9	21.7
	C	3.2	0.4
	M	25.1	4.3
	A	-80.4	21.7

The CC_1 metamodel has an R^2 value indicating that it is able to account for 53.6% of the variability in CC. The main difference with the previous main effects models (RT_1 and NF_1) is that both categorical variables indicating autonomous coordination mechanisms (A and R) are included. While A was removed from the previous models, due to the fact that it results in no significant change or RT or NF, it is seen here as having an effect on the number of messages; indeed, a negative effect. This is a significant finding, because it indicates that while performance in terms of response effectiveness is the same regardless of whether assignment uses mediated or autonomous distribution, the latter is less costly in terms of the message exchanges it requires.

While we would also expect that autonomous rescue coordination effects a reduction in CC, the opposite effect is seen in the coefficient for R. This is, however, a result of the increased response time (as seen in metamodel RT_1) which will require more communication overall, despite the fact that is requires less communication in the same amount of time.

The fact that the number of medics (M) increases the number of messages by 25 on average for every additional medic suggests that this is the number of messages exchanged on average by any medic. This fits with the graphical analysis (see Figure 6-2.b) showing the main effects of medics on the number of messages exchanged within the medical discipline (IM) of about this magnitude and no change for the other types of messages. On the other hand, firemen (F) are removed from the model CC_1 given that the increase in the number of messages exchanged in the fire discipline (FM, also in Figure 6-2.b) is "evened out" by the opposite effect it has on the number of medical and interdisciplinary messages (MM and IM), which is an effect of the reduction in response time. Accordingly, we will not follow the same strategy as with dummy variables and will re-include F for the interaction effects model, since it will clearly show an effect when interacting with other factors.

The results of the backwards selection method for regression are contained in Appendix D. The selected metamodel with interaction effects (CC_2) can be seen in Table 6-13.

augmented with interact-tion effects.

Table 6-13 Main effects model for coordination cost (CC) augmented with interaction effects

Model		Coefficient	Std. Error
CC_2	(Const)	126	94
$R^2 = 0.736$	C	2.4	1.2
	F	23	5.7
	R	-340	88
	C*F	-0.22	0.07
	C*R	4.45	0.66
	F*R	16	3.3
	A	623	73
	C*M	0.25	0.07
	F*A	-32	3.3
	M*R	28	6.4
	M*A	-17.4	6.4
	A*R	-185	33

Since coordination is measured in terms of message exchanges between the response agents, we can look at how autonomy can impact those message exchanges. Considering the firemen (F), each additional fireman produces on average 23 messages, 16 more if rescue is autonomous (F*R) but 32 less if assignment is autonomous (F*A). This confirms the findings from the main effects model that indicate that while autonomous rescue increases the number of messages by severely increasing the response cycle, autonomous assignment of firemen (which performs the same as mediated assignment in terms of RT and NF) can reduce it. In this case, this depends on a high number of firemen (to offset the coefficient of A) but in combination with mediated rescue it should produce the most reduction in CC.

6.4 Experimenting with the Metamodel

The metamodels are used for experimenting with…

Metamodels obtained through design of experiments contributed to understanding the real-world problem situation by providing screening of the most important factors and showing the main effects and interactions between factors (*ibid.*). They can now be used to gain additional insight through experiments aimed at the original research questions, concerning response values for different coordination mechanisms. It should be noted, however, that those specific values are not meant to be predictive, but rather exploratory, so we are interested in magnitude and relative values, not on specific numbers, hence we will focus our analysis on graphical results. In order to contribute to answering research question 2 (RQ2 in Chapter 1) we will use the metamodels augmented with interaction effects (RT_2, NF_2 and CC_2) for gaining exploratory insight into the use of mediated vs. autonomous coordination in crisis response. It should be noted that the additional insight obtained from the use of the metamodel is limited to the originally defined domain of applicability (see Table 6-4) and should thus be carefully placed in context before applying it in practice.

assignment coordination …

In terms of response time, we have already determined that assignment coordination has no impact, regardless of whether it is mediated by the Fire Officer (OvD) or autonomously determined by each Fireman – it should be noted, however, that both mechanisms do have an effect, otherwise firemen would never cease fire fighting to aid with rescue. Indeed, there is no A factor in RT_2 (see Table 6-9) or NF_2 (see Table 6-11). We can thus conclude that within the context of our experimental domain:

(Insight 1)

In terms of response time (RT) and number of fatalities (NF), there is no significant difference in coordinating assignment of firemen between fire fighting and rescue (A) regardless of whether the coordination mechanism is mediated or autonomous.

and rescue coordination, in terms of…

However, there is a significant improvement in terms of coordination cost when using autonomous assignment. We can use the CC_2 metamodel in order to generate experimental results in a much faster way than using the original simulation model, keeping in mind that every simulation run takes about 2 minutes and resetting the agent platform in between runs can take several minutes while the agents are "killed" and a new container is deployed. This is a convenient and simplified way of obtaining results, enabled by the metamodel – albeit, with a higher level of abstraction than the original simulation model. Given that the number of civilians is not something that crisis response organizations can control, we maintain the number of civilians fixed at the original "Low" value of 50 (see Table 6-4). In order to obtain more refined data about coordination cost, we vary the number of Firemen (F) between 1 and 20, and the number of Medics (M) between 1 and 10. For these and all subsequent scatter plots, we create 10 data points for each fireman or 20 for each medic, using the corresponding metamodel. Based on the values of these 10 or 20 data points, we indicate the "sensitivity" of the data point for the number of responders in the other discipline, expressed as a 95% confidence interval, to give a graphical measure for the 'spread' introduced by the number of other responders (as error bars for each mean data point. The scatter plots for each of the four coordination combinations (changing both A and R between 1 and 0) for coordination cost against the firemen can be seen in Figure 6-3, while Figure 6-4 is set against the medics.

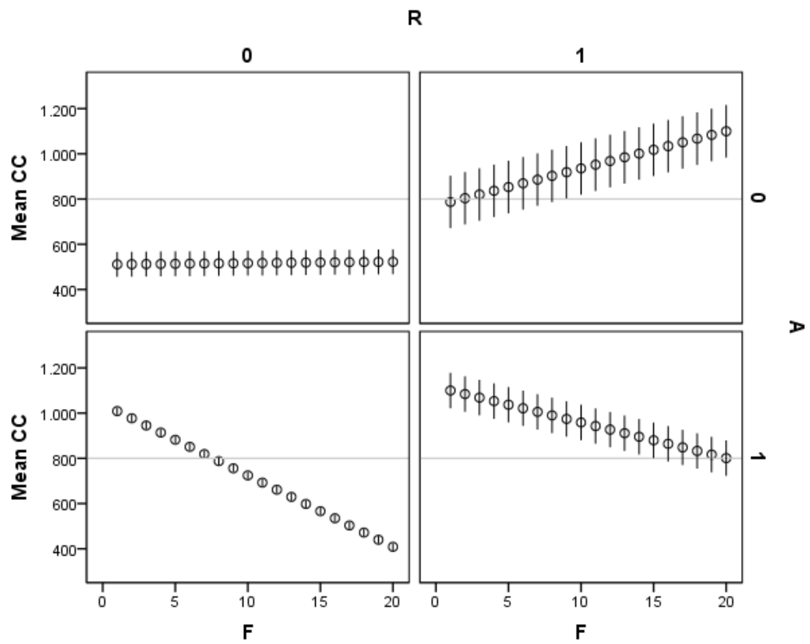


Figure 6-3 Scatter plots of Coordination Cost against Firemen (CI= 95%)

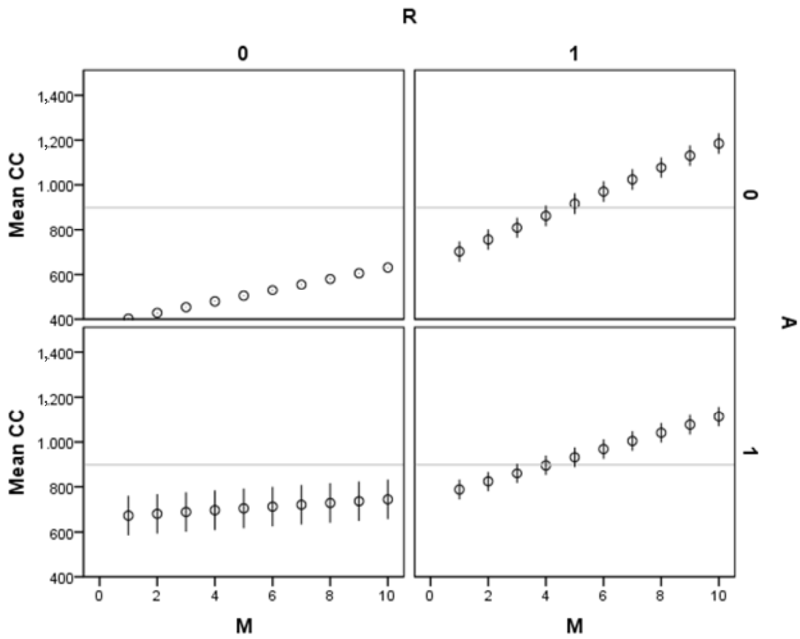


Figure 6-4 Scatter plots of Coordination Cost against Medics (CI= 95%)

coordination cost.

If we focus on autonomous rescue coordination against firemen (A=1, as compared to A=0 on Figure 6-3) it can be seen that autonomous assignment is less costly than mediated assignment, especially as we increase the number firemen (which makes sense considering that assignment is aimed at firemen, not medics). If we also consider rescue (R in Figure 6-3), we can see that mediated assignment (A=0) has no effect if rescue is mediated (R=0) and that the worse case (in terms of coordination) is a combination of autonomous rescue and mediated assignment (R=1, A=0), reflecting the interactions between A and R (e.g. A*R in metamodel CC_2).

In relation to the number of medics (Figure 6-4) we can observe that coordination cost increases for all combinations, though the least increase rate (the less steep line) is obtained with mediated rescue and autonomous assignment (R=0, A=1). Overall, mediated rescue (R=0) results in lower coordination cost on average. The fact that coordination costs always increases as the number of medics increase, regardless of the coordination mechanism employed, reflects the fact that the only coordination mechanism relevant for medics (R) is shared with firemen and as such depends on the relative number of firemen and the way they coordinate among themselves and with the medics. Accordingly, we obtain the following insight.

(Insight 2)

The interaction between assignment coordination (A) and rescue coordination (R) indicates that one coordination mechanism can influence the performance of another. This suggests that emergence of coordination is a result of the interaction of all coordination mechanisms employed during crisis response.

(Insight 3)

The configuration of coordination mechanisms which is capable of reducing coordination cost the most is mediated rescue (R=0) and autonomous assignment (A=1).

Rescue coordination with a shared data space…

We continue using the other two metamodels (RT_2 and NF_2) to obtain insight on the use of mediated rescue through a shared data space (SDS). This enables an experimental exploration of the benefits of using a simple ICT tool that supports rescue coordination. Before that, let us recall that such SDS consists in a central repository (a flexible list) which all responders can access to send (write) the geographical coordinates of a selected victim or to check (read) whether the selected victim is already on the list and proceed with a new selection (provided that the responder can observe an additional victim). Such a SDS is relatively easy to implement in real life with the use of GPS devices, increasingly available in mobile phones, portable computers and even digital cameras or sophisticated wrist watches. Indeed, while the SDS is kept very simple (only the coordinates are sent), it is possible with portable applications (such as Google Maps or Nokia Maps) to visualize those coordinates at the local responder level. Moreover, the SDS list can be used by the CoPI team to observe the position of victims as they are added by the responders, without having to request such information explicitly. While the individual responder will use this SDS for coordinating rescue with other responders, the operational command, control and coordination team can use it to get the global view of the victims as observed by the responders and, perhaps more importantly, the dynamic change in the victims location and number as they are rescued. All this can contribute to improving the information quality, especially in terms of providing a common format and an accurate and complete description of location that is consistent by being (logically) centralized.

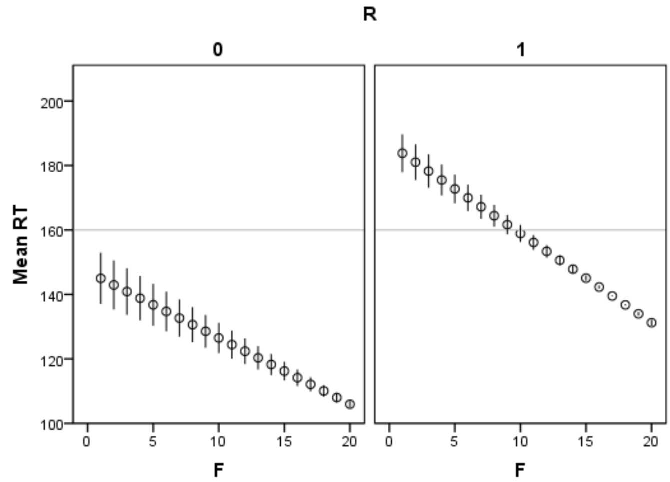
In addition, it should be noted that such ICT support for coordination can be setup very quickly without the need for extensive development or use of additional standards. In fact, such a tool can be generalized to rescuers regardless of their discipline, even encompassing volunteers. The only requirements are having a device enabled with GPS capabilities and of course the satellite communication required to determine the coordinates. These are both technically feasible options and offer more reliability over solutions that depend on a wired infrastructure which may become damaged as a consequence of the crisis.

is used to asses the value of ICT support…

First, we can gain insight into the improvement that such ICT support for coordination can have in response time in relation to the other factors provided by the metamodel (RT_2). Using the same factor setting as the previous set of plots, we obtain the following scatter plots for response time in Figure 6-5.

in terms of response time…

(a) RT against F with mediated (R=0) or autonomous rescue (R=1)



(b) RT against M with mediated (R=0) or autonomous rescue (R=1)

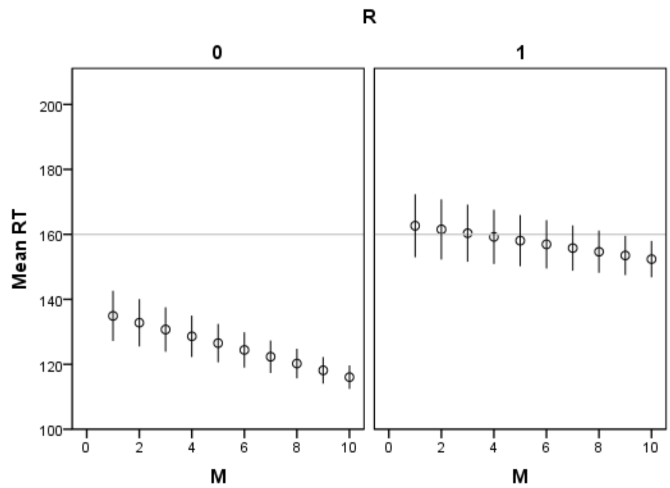


Figure 6-5 Scatter plots of Response Time against F and M (CI= 95%)

The two sets of plots show a similar trend for response time both when the focus is placed on Firemen (Figure 6-5.a) and Medics (Figure 6-5.b) indicating a reduction in response time when using mediated rescue (R=0), which is expected according to the coefficient for R in RT_2 which has a high magnitude with a positive sign (note that in the metamodel R refers to autonomous rescue which has the opposite effect and hence increases RT).

However, interaction effects are also present and can be observed in the plots. First of all, if we consider the error bars, it appears as if they are shrinking as we increase the number of responders (indeed, the deviations from the mean are a result of varying the number of responders for the other discipline). This is a way of indicating the interaction that exists between the number of firemen (F) and medics (M) with the obvious implication that for a low number of firemen, a higher number of medics improves response time, and conversely for a low number of medics a higher number of firemen improves response time.

In relation to rescue coordination (R) it can be seen that this "shrinkage" occurs faster when rescue is autonomous (R= 1 in Figure 6-5.a). This suggests that mediated rescue by using a shared data space not only improves average response time, but also the individual contribution of responders from the other discipline (M) which can still make a difference for a larger number of firemen, making the response organizations scalable up to a higher number of responders. Notice, however, that this cannot be seen as easily for the set of plots focusing on an increased number of medics (Figure 6-5.b), since the individual contribution of medics is "offset" by additional firemen, given that they can act as support for the medical rescue operations. We thus can support the following statements:

(Insight 4) *When victim rescue (R) is coordinated through the mediation of a shared data space, a significant improvement (reduction) in response time (RT) can be obtained, as compared to autonomous coordination of rescue.*

(Insight 5) *If victim rescue (R) is coordinated through the mediation of a shared data space, the individual contribution of responders (F) to reduction of response time (RT) is more significant than with autonomous coordination of rescue.*

and reduction of fatalities.

Further evidence and insight about the effect of using a shared data space for mediating rescue can be obtained by analyzing the results of the same factor settings using the last metamodel available (NF_2). The scatter plots for this last response can be seen in Figure 6-6.

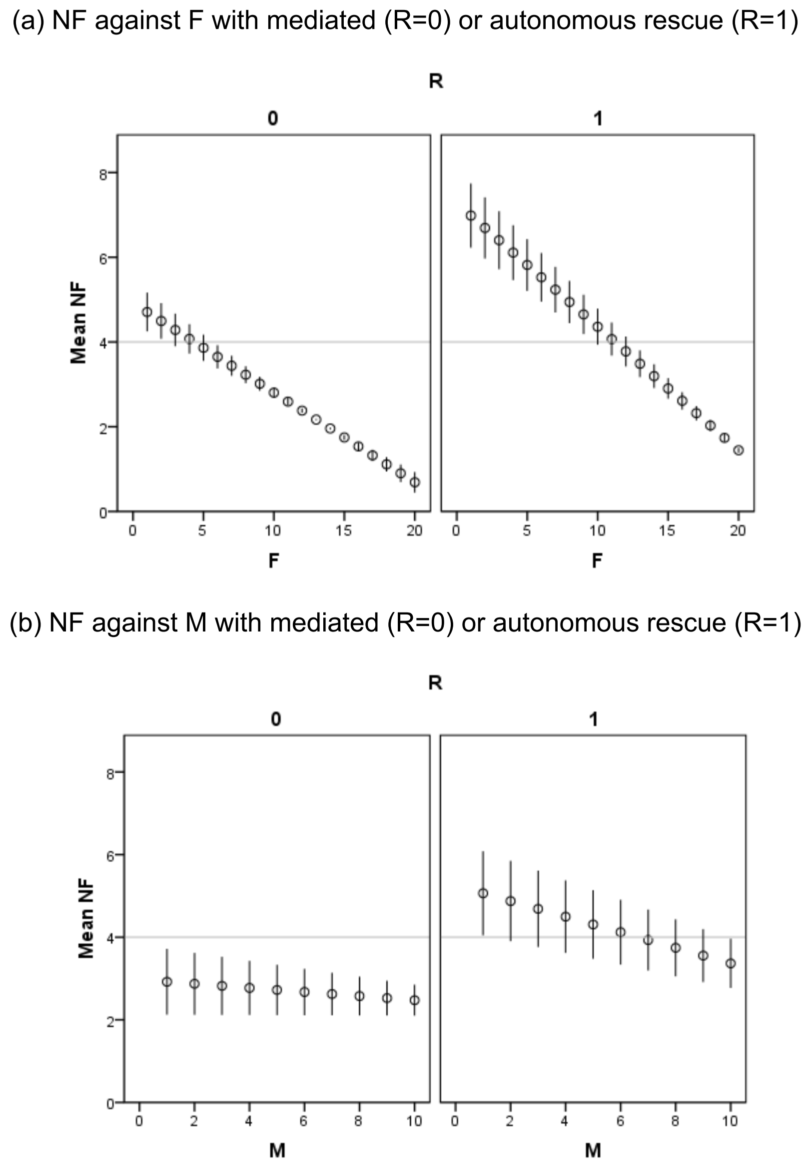


Figure 6-6 Scatter plots of fatalities (NF) against F and M (CI= 95%)

As expected, Figure 6-6 shows a similar effect on number of fatalities (NF) as in RT when considering rescue coordination. In fact, rescue coordination (R) has the largest coefficient in NF_2. However, R also has a large standard error and this can be seen in the plot as an effect of the number of responders which have a direct impact on NF, especially with a low number, where the error bars are wider. This indicates, as can be seen in the metamodel, that NF depends on the interaction between the number of civilians (C), the number of responders (F, M) and the way in which they are coordinated (R), showing multiple interactions between those factors (C*F, C*M, C*R, M*F, F*R, M*R). The key then is to have a response organization proportional to the number of civilians estimated on the scene and provide them with an effective coordination mechanism (in this case, a shared data space) so that their efforts will not be redundant and ineffective.

Once again, the effect of mediated rescue not only enables more victims rescued in less time (and hence less fatalities), but also shows that individual contributions remain significant for a larger number of responders that when using autonomous rescue (and here the effect can also be seen for medics, which was not apparent in terms of RT). Accordingly, the insight from the experiments is equivalent to that for RT:

(Insight 6)

When victim rescue (R) is coordinated through the mediation of a shared data space, a significant improvement (reduction) in the number of fatalities (NF) can be obtained, as compared to autonomous coordination of rescue.

(Insight 7)

If victim rescue (R) is coordinated through the mediation of a shared data space, the individual contribution of rescuers (F and M) to reduction of fatalities (NF) is significant up to a higher number of responders, when compared to autonomous coordination of rescue.

6.5 A Reflection on the Use of Metamodeling

Meta-modeling with regression analysis…

Metamodeling is one way to get insight out of experimental simulation data. It may be noted that this reflects a particular understanding of metamodeling, where a metamodel is a statistical regression model. As Allen (1997, p. 4) holds, "it is important to bear in mind that regression analysis is nothing more than a mathematical model for describing and analyzing particular types of patterns in empirical data".

requires an appropriate experimental design,

In combination with an appropriate design of experiments, regression analysis offers a tool for abstracting the effects of certain factors on certain responses, as well as their interaction effects. This enables the researcher to obtain sharp insights out of the patterns obtained from the regression analysis in a direct and rigorous manner. While the insights can of course be obtained from the simulation data itself – indeed, regression analysis is merely a tool for analyzing the data produced by the simulation experiments – using metamodeling enables the researcher or analyst to design the experiments in such a way that the resulting data can be directly and completely processed and captured by a meta-model that acts as a simplified version of the original simulation model, focusing on the desired factors, their effects and interactions. This is even more straightforward and easy to process and interpret when the experiments follow an orthogonal design and when the data can be input into a statistical analysis software package. In our case, the experimental design resulted in five factors with two levels each. This design implies a set of 32 experiments (each with 10 runs) that provides a complete input for the regression analysis aimed at a linear regression model with interaction effects. Of course, with more factors and more factor levels, the experimental design becomes more complex, affecting the ensuing regression analysis. There must then be a tradeoff between the complexity of the design and the desired analysis, but in certain cases it will not be possible or desirable to limit the number of factors and factor levels.

Equally important is the completeness of the experimental data. In our case, having complete control over the experiments allowed us to have the full set of 320 data points, but other models or experiments may limit the capacity of the researcher to obtain a complete set. While there are techniques that can help in dealing with incomplete or unbalanced data, having a complete set results in better metamodels and direct automated analysis through software. Simulation is particularly beneficial, in the sense that, save for computational power or effort in designing and running the experiments, there are no limitations in obtaining data, which are often prohibitive for carrying out regression analysis based on data collected from the real world.

a manageable dataset,

Because simulations, especially those built with agent-based models, can produce second or higher order effects between factors, regression analysis may result in either linear regression models, linear regression models augmented with interaction effects, or higher-order regression metamodels. While the latter tend to produce increasingly better fitting models and may uncover non-linear interaction effects between factors, it is also the case that such models may require more complex designs of experiments. In addition, the resulting models are more complex themselves and it becomes increasingly more difficult to extract, to explain and to interpret such effects. A first-order polynomial regression model augmented with interaction effects of the kind used in our metamodeling effort is a good compromise between simple first-order polynomials which miss interaction effects and higher order polynomials which are harder to interpret and need many more simulation runs (Kleijnen, 1999b).

and high-order effect considerations,

Nonetheless, this compromise needs to also consider its potential limitations and carry a warning to other researchers in the field of agent-based simulation. As non-linear effects are often a key phenomenon in complex adaptive systems, many agent-based models pursue such effects via feedback and adaptation (e.g. Macy & Willer, 2002). While the goal of agent-based modeling is to produce such nonlinear effects through simple bottom-up aggregation of local interactions, regression analysis of the data produced by the simulation experiments may not be as easy, given the need to use higher-order polynomials and more complex experimental designs. In our case, the agents are not designed to be adaptive, in the sense that they cyclically follow the same finite-state machine behaviors throughout the duration of each run. However, a metamodel can still be unable to capture certain effects and interactions given that a specific set of factors has been chosen. Those effects that are not captured by a particular metamodel are, in any case, reflected in the associated R^2 value, or coefficient of determination, and any insight obtained by a given metamodel should be considered stronger as this value gets closer to 1.

particularly when using agent-based models.

In terms of the overall research approach, metamodeling is placed inside the *design cycle* as a way to obtain insight, including unexpected effects of certain factors on the key performance indicators. By uncovering the patterns in the data, the regression models offer a simple description of the effects and interactions of individual factors, which may go unnoticed, and provides the magnitudes for forcefully asserting those patterns. This produces sharp quantitative assertions that constitute the basis for theoretical insight into coordination during crisis response. For example, against expectations embedded in the design, autonomy sometimes proved equal or better than mediation. Furthermore, the effects of interactions resulting from combining coordination mechanisms only become evident after the simulations are run and the regression analysis helps in abstracting and extrapolating after several runs in a systematic way. Such insight

In design science, the resulting metamodels distills the main contributions of the simulation model to revising and extending the kernel theory related to the information-processing view of coordination. As with any theoretical insight resulting from simulation experiments, the assertions are limited to the experimental domain and should be contextualized within the set of constructs, models and methods employed in the design of the simulation model.

can be used for gaining insight.

A positive effect on the rigor of design science research in information systems is the ability to obtain insight that is susceptible of repeatability and cross-validation, given the quality of a polynomial representation in expressing main effects and interaction effects. It should also be noted that besides the insight expressed via the regression metamodels, other theoretical contributions, from a design science point of view, are contained in the design knowledge employed, as summarized earlier in this chapter on Table 6-1. The verification and validation of the simulation model provides a measure of confidence in the model as a starting point for obtaining the insight which the metamodeling effort expresses. Nonetheless, the empirical validation of the insight remains beyond the scope of the design cycle completed in this research. Subsequent validation is possible, both in terms of additional refined design cycles and eventually of empirical validation through real life data; however, this will continue to be a difficulty in the field of crisis response, which is why simulation is used in the first place.

7 Epilogue

Recently, the earthquake in Haiti has become a tragic example of a large-scale crisis event for which coordination of the response has proven once again to be one of the biggest challenges for response and rescue operations (McGreal & Addley, 2010). The almost collapse of the local government and the intervention of military personnel from the UN, the US, and other countries resulted in a lack of clarity with regards to the leadership and control of the relief efforts. While planes arrived from all over the world carrying aid, supplies often remained sitting at the airport due to faulty logistics, lack of security, mutual finger pointing and conflicting priorities. In such situations, it is easy to see the critical relevance that efficient and effective coordination has on successful crisis response.

Coordination is still a challenge for crisis response.

Using ICT for supporting coordination during a crisis is a way of dealing with this challenge. However, given that the crises and their corresponding *ad hoc* crisis response organizations are still unknown, we have to rely on planning, training and simulation in order to increase our understanding and preparedness. In particular, using agent-based modeling is a suitable way to represent heterogeneous, autonomous crisis responders, enabling the simulation of aggregate behavior out of local agent behaviors. Within such a model it is also possible to operationalize different coordination mechanisms that could be supported with ICT in order to compare and evaluate them in an artificial setting, before moving on to training, planning and actual use during a crisis. One such model has been designed in the previous research, together with the set of constructs, models and methods that went into its construction and experimental design. Together, these artifacts provide a conceptual framework and the design knowledge required to build agent-based simulations for the study of coordination in crisis response. The specific instance developed was used to compare between autonomous and mediated coordination mechanisms in a specific crisis scenario, resulting in a set of findings around the initial research questions.

7.1 Findings

The first research question (RQ1) referred to the extension of the current understanding of coordination in crisis response. From the *relevance cycle*, the importance of this question was established in Chapters 1 and 3. While Chapter 1 determined the unavoidable presence of emergence coupled to the shortcomings of current coordination practices during crisis response, Chapter 3 explored the empirical content of the information-processing view of coordination and its limitations in accounting for emergent coordination.

Findings address: research question 1, From the *rigor cycle* we obtained the kernel theory and the additional design knowledge required to enter the *design cycle*. Chapter 2 determined that the information-processing (I-P) view of coordination has been widely used to guide the discussion and research on coordination in the crisis response domain. However, it also presented several critiques that have been raised to revise or extend this understanding, including: collaborative coordination, behavioral theories, situated coordination, governance views of coordination, "role-based" coordination, and "practice-based" coordination. These alternatives address the influence of emergent behavior on coordination during a crisis or in fast-response *ad hoc* organizations, such as those that form after a crisis event to respond to it. However, they do not provide a full account of what exactly is meant by "emergent coordination" in this context. Accordingly, Chapter 4 focused on the adoption of notions from complex adaptive systems (CAS) within the crisis response domain. Emergence can thus be understood as a central property of (agent-based) dynamic systems which results from confronting the agents within a specific structure of interaction constitutive of both the agent and system levels. The consequence is that agents should be used as an analytical unit for the study of coordination in crisis response. In relation to the I-P view, this led to the recognition of mutual adjustment as representing coordination in practice, while also being embedded within an organizational structure that includes standards and mediation.

In the *design cycle*, an agent-based simulation model was built for gaining insight into coordination in crisis response, as proposed in Chapter 5, under the assumption that the relation of a designed artifact to theory is extension and refinement rather than disconfirmation. The conceptual model for the simulation operationalized constructs from the I-P view of coordination and the CAS-based notions from Chapter 4. This fits with the development of agent-based simulations which are often derived from the interaction of multiple theories; while this potentially violates the *ceteris paribus* assumption behind natural science, theory development with agent-based simulation does not require theoretical isolation, but rather encourages development across multiple levels of analysis and with multiple theories, while maintaining control over the variables (Louie & Carley, 2008).

regarding theoretical insight;

The interaction of the I-P view with agents and emergence resulted in the following insight. Since a crisis is defined by uncertainty (see Section 1.3), from an information-processing view this suggests that mutual adjustment should be the dominant coordination mechanism (see Section 2.4). Nonetheless, the presence and support for hierarchical organizations and plans in practice (see Section 3.3) still emphasizes standards and mediation. But there is an increasing recognition that this can have poor results; indeed, in The Netherlands during the acute phase of a crisis, "central controlled coordination cannot be achieved" (Scholtens, 2008). The decision to use agent-based simulation is a recognition that decentralized, mutually adjusted coordination should be understood and supported, instead of neglected, while at the same time providing a testbed to compare mutually adjusted mediation to centralization in specific crisis conditions, under the assumption that both will be present. Coordination mechanisms in crisis response should thus not be treated as mutually exclusive, but as mutually related, which favors the use of agent-based simulation to evaluate, compare and gain insight into their effects and interactions.

The second research question (RQ2) then asked about precisely this comparison between centralized coordination (stemming from command-and-control approaches to crisis response) and decentralized coordination (stemming from emergent or net-centric approaches to crisis response). We obtained insight into this question by performing metamodeling and experiments with the simulation model. The graphical analysis of a set of 32 experimental scenarios provided some initial insight. Interesting cases from the experimental design suggested that poor performance (within our experimental domain) is to have autonomous decentralized rescue coordination and mediated assignment coordination, when there are a large number of responders. More generally, the least effective results, in terms of response time, victims and message exchanges, were obtained with a high number of civilians, a low number of medics and firemen, and the use of autonomous rescue. This shows that there is no unique answer to the question of "which is better, mutual adjustment or mediation?", since it depends on the specific coordination dependency and the interaction with other contextual factors. Furthermore, whether a coordination mechanism is enabled by ICT or not can also result in different performance (as we will see in the answer to our third research question).

research question 2,

By performing more refined experiments with the metamodel that resulted, further insight was obtained. This insight is limited by the domain set out in the design of experiments and includes: (1) In terms of response time and number of fatalities, there is no significant difference in coordinating assignment of firemen between fire fighting and rescue regardless of whether the coordination mechanism is mediated or autonomous. (2) The interaction between assignment coordination and rescue coordination indicates that one coordination mechanism can influence the performance of another. This suggests that emergence of coordination is a result of the interaction of all coordination mechanisms employed during crisis response. (3) The configuration of coordination mechanisms which is capable of reducing coordination cost the most is mediated rescue and autonomous assignment.

regarding coordination mechanism comparison;

The third and last question (RQ3) then asked about how the extended understanding of coordination could be used to bridge the gap between the possibilities and realities of ICT support for coordination during a crisis. First of all, in the *rigor cycle* (see Section 2.5) it was established that ICT can increase information-processing capabilities, but can also introduce new coordination costs. In the first case study (see Section 3.3) it was shown how different ICT tools are used in the Port of Rotterdam for supporting crisis response (including telecommunication, integrated systems, geographic information technologies and workflow simulations) and that these can support different coordination mechanisms and be used outside the expected standard manner. The second case study (see Section 3.4) then made the argument that coordination can be improved through the inclusion of information management services that support information quality (accuracy, timeliness, relevance, quantity, completeness, format, security, and consistency); hence, a shared data space (SDS) was selected for inclusion into the simulation, as an illustration of ICT use to support coordination / information quality.

and research question 3,

The simulation model then enables gaining insight about the contextualized uses of the ICT and provides a setting for evaluating them prior to testing in the field – which also fits with how artifacts should be evaluated in lab settings within the *Design Cycle* of design science research. The experiments with the metamodel provided the following insight regarding the use of the SDS to support coordination: (4, 6) When victim rescue is coordinated through the mediation of a shared data space, a significant reduction in response time and fatalities can be obtained, as compared to autonomous coordination of rescue. (5, 7) If victim rescue is coordinated through the mediation of a shared data space, the individual contribution of rescuers to reduction of response time and fatalities is significant up to a higher number of responders, when compared to autonomous coordination of rescue. Finally, it should be noted that while the SDS represents mediated coordination, an agent-based implementation can actually imply a decentralized use of ICT with similar (but more resilient) results (see agent technology support for crisis response in Section 1.4).

regarding ICT support.

7.2 Research Approach

Design science research….

The discussion around rigor vs. relevance in information systems research (ISR) has been around for some time, focusing on the nature of ISR, on the interaction between researchers and practitioners, and on the tension between the design of information technology (IT) artifacts and the development of theory, among others. While some have provided recommendations for increasing the relevance of ISR outputs (Benbasat & Zmud, 1999; Gill & Bhattacherjee, 2009), others have provided suggestions on how to improve the rigor (Boudreau, Gefen, & Straub, 2001; Lee & Hubona, 2009). The increasingly used and accepted design science research in information systems (DSRIS) provides a framework for ISR which is both rigorous and relevant (Hevner *et al.*, 2004; Winter, 2008).

proved useful, but can still…

Through Hevner's (2007) three-cycle view of DSRIS, relevance and rigor are attached to specific cycles that are materialized inside a *Design Cycle*. This proved useful for this research, where the *Relevance Cycle* was achieved through an exploration of coordination issues in crisis response literature and through two case studies that added empirical content. The *Rigor Cycle* identified the information-processing view of coordination as the dominant theoretical framework for studying coordination in crisis response, and was used as analytical framework in one of the case studies. A second iteration through the knowledge base extended the information-processing view with notions from emergence and agent-based modeling. The set of relevant issues and requirements could then be tackled using the constructs, models and methods from the *Rigor Cycle* in the construction of a simulation model inside the *Design Cycle*. Simulation fits within this cycle as it enables an iterative development of the simulation model as well as allowing for testing through experiments that can further feed back on the design, while at the same time providing contributions to the knowledge base and practical implications for the relevant environment.

However, compared to more established research approaches, DSRIS is relatively young and thus exhibits some open issues. Previous chapters argued the lack of agreement regarding the role of theory and theorizing within DSRIS, the lack of a common epistemological grounding, and the lack of consensus with respect to how DSRIS contributions should be evaluated and validated. In addition, while some efforts have been made to make more explicit methodical guidelines about how to carry out DSRIS (e.g. Peffers *et al.*, 2007), there is still a lack of convergence in the way individual DSRIS projects should be executed.

increase maturity,

Despite these gaps, the potential shortcomings are far outweighed by the fact that DSRIS is being developed with ISR in mind – although design science research can also be employed in engineering, design, architecture, medicine, and management science. Moreover, these open ends are related to each other in the sense that a particular epistemology should guide the development and validation of the contribution. Furthermore, the fact that DSRIS remains open helps achieve rigor, without compromising the creativity that should go into designing any artifact for a relevant environment. Any DSRIS contribution should make the choices about these issues explicit, which should allow judging the contribution as well as enabling a more systematic learning process about design science research.

through openly documented assumptions.

7.3 Further Research

The contributions made in previous chapters are not without their limitations. While using the three DSRIS cycles proved useful in conceptualizing the research and maintaining the link between the environment and the knowledge base through the design, it is also the case that each cycle is open ended, since at each cycle the requirements, the knowledge and the design change. This encompasses an iterative approach to problem solving, but also implies an inherent lack of closure when dealing with ill-structured complex problem situations. Given the limitations and challenges of doing research in crisis response also adds to this openness, specifically in terms of field testing. Firstly, field testing in crisis response is limited given the unpredictability of a crisis incident and of the potential users of crisis response support tools. Secondly, to actually deploy tools in the field responsibly requires a team capable of providing support and maintenance during a prolonged period of time.

Further research includes:

Using simulation provides the possibility of testing tools and coordination policies in a controlled environment without the limitations of field testing. Additional scenarios can be developed for testing in different types of crises. The simulation model architecture has been designed with this consideration in mind in order to allow for separate additional crisis scenarios to be developed for the same configuration of the crisis response organization and vice versa. Accordingly, developing new crisis scenarios on the one hand, and new responders, behaviors and coordination mechanisms on the other, would allow for an extended application of the simulation model. In particular, developing larger scale, multiple incident scenarios would be a natural progression of the discrete-event side of the model.

developing new crisis scenarios,

With regards to the agent-based model of the crisis response organization, extending the behaviors of the agents should be possible through the inclusion of more realistic and refined models obtained from behavioral studies of responders.

extending the response organization model and

In addition, the capabilities of the agents can be extended with more intelligence. Without major changes, it is possible to design new experiments aimed at getting additional insight about different factors. For instance, *timeouts* and *sleeps* within the agents have been kept constant, but they could be tailored for specific agent profiles. Certain agents could be faster in processing information when aided by ICT or a patience attribute can be attached to the officers to determine how long to wait for replies from their responders. In addition, the observations sent by the responders all carry with them a timestamp and a sender ID; at the moment all are given equal importance, but the officer behavior can be adjusted to attach a particular weight or credibility to the assessments based on the credibility of the responder or the timestamp of the reply. Such extensions would require input from experts in different academic and emergency-related disciplines. With such input invested into subsequent design cycles, the model can be transformed from an exploratory simulation model aimed at gaining insight through operationalization of the design knowledge, into a multi-agent system that can support real crisis responders in practice by offering certain information processing capabilities that can be unloaded from the user. Before such support is used, however, evaluation should be carried out thoroughly in laboratory or training scenarios under different crises conditions.

revising our notion of "agents".

From the point of view of agent technology, the very notion of agents seems to be reaching maturity. As pointed out in Chapter 4, the agent construct is underpinned by distributed artificial intelligence (DAI) and complex adaptive systems (CAS). From a DAI point of view the emphasis originally tended towards relatively complex agents for supporting mainly information gathering and processing on behalf of a third party. Within CAS the emphasis was on the aggregate system-level behavior obtained from the interaction of simple agents. However, the two understandings have been learning from each other, giving rise to agent-based modeling and simulation as a field in its own right not dependent either on DAI or CAS exclusively. In the construction of our simulation model, the agents are neither too simple nor too complex and while the emphasis is placed on coordination, each agent is enabled by the capabilities provided by the JADE platform, regarding mobility, autonomy and communication based on standardized protocols. Essentially, at the technological level, the agents are actually *objects* (in the object-oriented programming sense) extended with agent behaviors and further embedded into a discrete-event simulation environment. As such, they constitute an example of the increasing convergence of concepts, methods and tools from distributed systems, modeling and simulation, complexity theory and even organizational design and sociology into the understanding of agents. This will continue to be an active and promising research front with applications in computer science, social science, economics and other fields.

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Appendix A. Requirements and Analysis

A1. Response Processes and Activities

To establish the emergency response processes that the response agents should use as a basis for their behavior standard processes were extracted from manuals and guidelines. To begin, we consider the totality of general response processes for disaster management in The Netherlands, as determined by the Ministry of Internal Affairs (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2003c). The basic categories and their associated processes are shown in Table A-1.

Table A-1 Emergency Response Processes

A. Source and effect containment (Bron- en effectbestrijding) Responsible actor: Fire services (regional commander)	1. Fire fighting and containment of dangerous substance emissions 2. Rescue and technical relief (assistance) 3. Decontamination of people and animals 4. Decontamination o vehicles and infrastructure 5. Detection (observation) and measurement 6. Warning the population 7. Clearing and providing access
B. Medical assistance (Geneeskundige hulpverlening) Responsible actor: Medical services (Regional Medical Officer)	8. Medical somatic-assistance 9. Preventive public medical care 10. Medical psychosocial-assistance
C. Justice and traffic (Rechtsorde en verkeer) Responsible actor: Police (Chief) and Justice Officer (for *)	11. Clearing and evacuation 12. Blocking and screening 13. Controlling traffic 14. Maintaining public order* 15. Identifying victims 16. Guiding 17. Criminal investigation*
D. Population care (Bevolkingszorg) Responsible actor: Municipal services (Mayor)	18. Advising and informing 19. Care and relief (opvangen en verzorgen) 20. Funeral arrangements 21. Victim registration 22. Preparing basic necessities 23. Registering damage 24. Environmental care 25. Aftercare
E. General and support processes (Algemene en ondersteunde)	26. Alarming (warning) 27. Communication 28. Logistics 29. Registration and reporting 30. Evaluation 31. Archiving

Interactions are drawn from the relationships between those response processes, also available in the manual (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2003c) and show in Table A-2.

Table A-2 Interactions Between Emergency Response Processes

Process	Related Processes
1. Fire fighting and containment dangerous substance emissions	11, 6, 8
2. Rescue and technical relief (assistance)	11, 6, 8
3. Decontamination of people and animals	1-7, 11, 8, 12, 24, 9, 18
4. Decontamination o vehicles and infrastructure	1-7, 11, 12, 13, 24
5. Detection (observation) and measurement	5, 6, 18, 11, 12, 3, 4, 24, 8
6. Warning the population	18, 11, 12, 6
7. Clearing and providing access	1-7, 8, 12, 13
8. Medical somatic-assistance	19, 21, 3, 4, 13, 10
9. Preventive public medical care	22, 21, 8, 10, 18, 1-7, 11, 17, 23
10. Medical psychosocial-assistance	22, 21, 8, 18, 11, 19, 20
11. Clearing and evacuation	5, 6, 18, 21, 13, 16, 7, 3, 19, 22, 12, 23, 10
12. Blocking and screening	11, 14, 13, 18
13. Controlling traffic	12, 16, 14, 18, 8, 11
14. Maintaining public order	1-7, 8, 19, 11, 17, 13, 12
15. Identifying victims	3, 2, 8, 21, 12, 17
16. Guiding	11, 13, 14, 19, 1-7, 8
17. Criminal investigation	1-7, 8, 15, 20, 14
18. Advising and informing	19, 21, 23, 6
19. Care and relief (opvangen en verzorgen)	11, 13, 12, 22, 21, 18, 8, 10
20. Funeral arrangements	8, 19, 21, 15, 17, 10
21. Victim registration	8, 15, 19, 18
22. Preparing basic necessities	11, 19, 21, 22, 9, 23
23. Registering damage	17, 22, 18
24. Environmental care	1-7, 17
25. Aftercare	18, 10, 9, 23, 21
26. Alarming (warning)	-
27. Communication	-
28. Logistics	-
29. Registration and reporting	-
30. Evaluation	-
31. Archiving	-

Filtering criteria

The first limiting criterion is based on the first chosen scenario, which corresponds to the training case described on the first vignette in Chapter 1. In order to determine the crisis type, we consider all those available in the Dutch crisis response classification (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2003b), shown in Table A-3.

Table A-3 Crisis Typology

Crisis type	Sub- types
Crisis concerning traffic and transport (verkeer and vervoer)	Aviation accident Water accident On land traffic accident
Crisis with dangerous substances	Accident with flammable explosive substance Accident with toxic substance Nuclear accident
Crisis concerning public health	Threat to public health Epidemic (ziektegolf)
Crisis concerning infrastructure	Accident in tunnel Fire in large building Collapse of building Collapse of public utilities
Crisis concerning the population	Mob panic Large-scale public disorder
Natural disaster	Flood Wild fire Extreme weather conditions

The basic scenario for the simulation is related to “On land traffic accident” type. On a second instance, it becomes an “Accident with flammable explosive substance” type. Finally, it becomes an “Accident with toxic substance” type. This last type is already a GRIP 4 incident and will be excluded from the model. This means we will focus on the first two disaster types (indicating a traffic accident and a big explosion with toxic fumes). The basic crisis scenario goes through four discrete phases (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2007a) described on the Vignette in Chapter 1. Furthermore, we limit the response processes to those appropriate for the type of disaster “On land traffic accident”. According to the Crisis Response Guiding Principles (Ingenieurs/Adviesbureau SAVE & Adviesbureau Van Dijke, 2000) on which the above response processes are based, Table A-4 specifies the required aid and size characteristics per process per discipline. This can be used as a source for determining the size of the crisis scenario as well as determining plausible sizes for the responder teams.

Table A-4 Crises Scales and Their Corresponding Required Aid

	Disaster type:	Accident with flammable explosive substance	Size				
			I	II	III	IV	V
			Central measure = victims (dead and T1+T2 type wounded)				
	Assistance Process	Specification of required aid per process	10	30	100	300	700
	1. Fire fighting and containment	requested pump capacity (meters)	400	450	600	1000	1800
	2. Rescue and technical relief (assistance)	# of persons to rescue	5	15	35	105	235
	3. Detection and measurement	surface to measure (km2)	p.m.	p.m.	p.m.	p.m.	p.m.
	4. Decontamination of people and animals	# of potentially contaminated citizens	p.m.	p.m.	p.m.	p.m.	p.m.
		# of contaminated rescue workers	p.m.	p.m.	p.m.	p.m.	p.m.
	5. Decontamination of vehicles	# of contaminated vehicles					
A. Fire	Indicated assistance from Fire		1	1	2	3	4
	1. Medical somatic-assistance	# of victims (dead and T1+T2)	10	30	100	300	700
		# of dead victims		5	20	60	140
		# of wounded (T1+T2+T3)	20	50	160	480	1120
		% wounded T1+T2	50%	50%	50%	50%	50%
		% wounded T3	50%	50%	50%	50%	50%
		% wounded by mechanical means	75%	75%	75%	75%	75%
		% wounded by biological/chemical/nuclear	20%	20%	20%	20%	20%
		% wounded by thermal means	75%	75%	75%	75%	75%
		% wounded by contamination	10%	10%	10%	10%	10%
	2. Medical psychosocial-assistance	# of persons with psychological aid needs		5	15	50	110
	3. Preventive public medical care	# of persons needing medication, vaccines/supplies		5	15	50	110
		collective medical investigation (# of persons)	100	250	800	2400	5600
B. Medical	Indicated assistance from Medical services		1	1	1	2	4
	1. Maintaining public order	persons present (passers by, crowd)	3100	3300	4000	6000	10000
		# of disturbers (plunderers, disaster tourists)	62	66	80	120	200
		# of instigators (hard to apprehend)	31	33	40	60	100
	2. Criminal investigation	# of persons to apprehend	31	33	40	60	100
	3. Controlling traffic	check points (together with blocking and screening)					
	4. Blocking and screening	check points	21	22	28	44	76
	5. Guiding	# of vehicles to guide	33	38	55	105	205
	6. Identifying victims	# of dead victims to identify		5	20	60	140
C. Police	Indicated assistance from Police		2	2	2	3	4
	1. Victim registration	# of persons to register	150	300	800	2200	5000
	2. Funeral arrangements	# of dead to bury/cremate		5	20	60	140
	3. Registering damage	material damage (m/n euro)	5	10	15	35	75
		# of victims		25	100	300	700
D. Municipal	Assistance from municipality		1	1	2	3	4

Filtered response processes

According to the filtering criteria, the initial process in Table A-1 is now limited to the following processes on Table A-5.

Table A-5 Filtered Emergency Response Processes

A. Source and effect containment (Bron- en effectbestrijding) Responsible actor: Fire services (regional commander)	1. Fire fighting and containment of dangerous substance emissions 2. Rescue and technical relief (assistance)
B. Medical assistance (Geneeskundige hulpverlening) Responsible actor: Medical services (Regional Medical Officer)	8. Medical somatic-assistance

Response Activities

The next step is to decompose the processes into activities and indicate which discipline is responsible (marked with a *) for the activity and which other discipline(s) intervene (marked with a +) in the activity. This is taken from (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2003a) and presented on Table A-6.

Table A-6 Activities for Filtered Crisis Response Processes

Process	Activities
Fire fighting and containment of dangerous substance emissions	1. Analysis of the situation 2. Drawing up plan for source containment 3. Communicating commitment plan 4. Getting available staff and resources 5. Deploying staff and resources 6. Supervising progress
Medical somatic-assistance	1. Analyzing information 2. Establish plan for medical assistance 3. Getting available staff and resources 4. Deploy staff and resources 5. Informing public, population and other interested parties 6. Evaluation of medical assistance.

A2. Preliminary Interaction Model

The preliminary interaction model captures the dependencies and relationships between the various roles in the MAS organization (Zambonelli *et al.*, 2003). Each interaction protocol is defined in terms of: Name, initiator, partner, inputs, outputs and description. Because in the liveness properties we have already identified which activities require interaction, these are the protocols that need to be addressed.

Table A-7 Preliminary Interaction Model

Protocol name	Initiator	Partner	Input	Output
InformFireAssessment	Fireman, Policeman, Medic	OvD, OvD-P, OvD-G	Site assessment	Message to commander
InformVictimLocation	Fireman, Policeman, Medic	OvD, OvD-P, OvD-G	Site assessment	Message to commander
InformAboutInfrastructure	Policeman	OvD-P	Site assessment	Message to commander
AnalyseFireSituation	OvD	OvD-P OvD-G CL	Nature, scope and expected evolution of fire; weather; infrastructure	Fire analysis
PlanContainment	OvD	OvD-P OvD-G CL	Fire analysis	Containment plan
DeployContainmentResources	OvD	Fireman	Containment plan, resources received	Resources deployed
AnalyseMedicalInformation	OvD-G	OvD OvD-P CL	extension, accessibility, object condition, victim condition, suspected number of victims, operational locations, critical points	Medical analysis
PlanMedicalAssistance	OvD-G	OvD OvD-P CL	Medical analysis	Medical plan
DeployMedicalResources	OvD-G	Medic	Medical plan, resources received	Resources deployed
InformMedicalSituation	OvD-G	OvD OvD-G CL	Medical assistance information	Customized reports on medical situation for public and other parties

Appendix B. Agent Design

B1. Role and Interaction Models

Role Models

Once the simulation model architecture is in place a revised model of the agent roles and their interactions (which can be found in preliminary format in Appendix A) can be designed. The role models for the Fireman, Medic, OvD, OvD-G and CL are defined in the following tables.

Table B-1 Fireman role model

Role	Fireman
Description	The Fireman is the Fire Services field agent in charge of fighting (suppressing) fires and rescuing victims.
Protocols & Activities	GetToLocation, NotifyArrival, AssessSituation, InformAssessment, UpdateAssessment, InformResult, ContainFire, MoveVictim
Permissions	Change Civilian. Read House. Read Vehicle. Change Fire. Change Responder (proxy simulated fireman: self)
Responsibilities	Liveness: FIREMAN=GetToLocation.NotifyArrival.(AssessSituation.InformAssessment. (Respond. UpdateAssessment. InformResult)*)* RESPOND = ContainFire | MoveVictim

Table B-2 Medic role model

Role	Medic
Description	The Medic is the Medical Services field agent in charge of assisting victims.
Protocols & Activities	GetToLocation, NotifyArrival AssessSituation, InformAssessment, AssistVictim, UpdateAssessment, InformResult
Permissions	Change Civilian. Read House. Read Vehicle. Read Fire. Change Responder (proxy simulated fireman: self)
Responsibilities	Liveness: MEDIC = GetToLocation.NotifyArrival.(AssessSituation.InformAssessment. (AssistVictim. UpdateAssessment. InformResult)*)*

Table B-3 OvD role model

Role	OvD
Description	The OvD (Officier van Dienst) is the officer in charge of the municipal Fire Services. As such, he should asses the situation; plan the response; supervise the carrying out of the plan by the field agents he leads; and coordinate with the officers from other services.
Protocols & Activities	GetToLocation, EstablishCoPI, CommunicatePlan, ReturnToCoPI, RequestAssessment, MergeAssessments, , InformPlanStatus, MultidisciplinaryConsultation, DetermineStrategy, DetermineLocations, DetermineRequirements, GetToLoadingPost, AlarmResponders, DeployUnits
Permissions	Read and Change inherited from Fireman role.
Responsibilities	Liveness: OvD= GetToLocation.(AnalyzeSituation. [EstablishCoPI]. PlanContainment*. CommunicatePlan. DeployContainment. ReturnToCoPI)* ANALYZESITUATION= RequestAssessment. MergeAssessments. [InformPlanStatus]. MultidisciplinaryConsultation PLANCONTAINMENT= DetermineStrategy. DetermineLocations. DetermineRequirements DEPLOYCONTAINMENT= GetToLoadingPost | |(AlarmResponders. DeployUnits)*

Table B-4 OvD-G role model

Role	OvD-G
Description	The OvD-G (Officier van Dienst - Geneeskundig) is the officer in charge of the municipal Medical Services. As such, he should asses the situation; plan the response; supervise the carrying out of the plan by the field agents he leads; and coordinate with the officers from other services.
Protocols & Activities	Same as OvD but leading medics
Permissions	Same as OvD but leading medics
Responsibilities	Same as OvD but leading medics

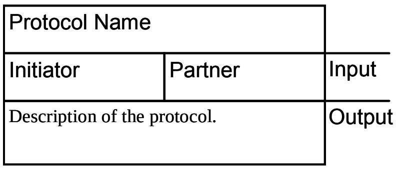
Table B-5 CL role model

Role	CL
Description	The CL (CoPI Leader) is the leader of the CoPI team made up of the OvDs from the three disciplines. Their main function is to act as coordinators between the municipal disciplines.
Protocols & Activities	EvaluateResponse, TerminateCoPI, CallForProposals, ProposalRevision
Permissions	Same as OvD
Responsibilities	Liveness: CL= (NegotiateProposals*. EvaluateResponse)*. TerminateCoPI NEGOTIATEPROPOSALS= CallForProposals. ProposalRevision

Interactions Model

The interactions model represents the interaction between the agents through the protocols previously defined for them.

The notation for the protocols is the following (Zambonelli *et al.*, 2003):



Protocols are then connected to illustrate the interaction in terms of input/output relationships and are grouped according to the highest level protocols. In this case, the protocols of the fire containment are chosen, but they are equivalent to the other disciplines. The following figure presents the interaction model initiated when the OvD requests an assessment of the situation from his responders.

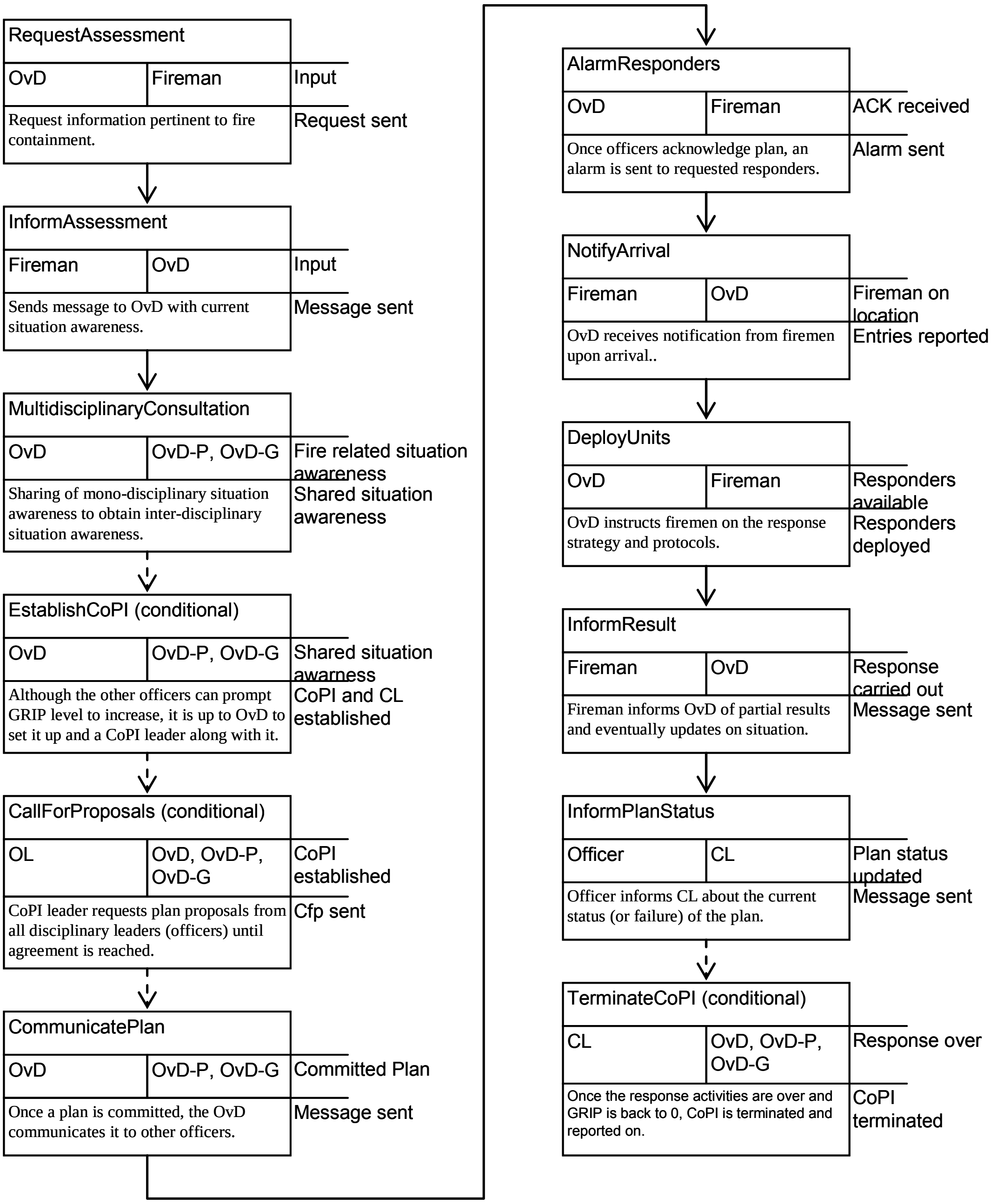


Figure B-1 Interactions model

B2. Domain Ontology

The domain ontology in Jade describes the elements that agent use to create the content of messages, specifically concepts, predicates and actions (Bellifemine *et al*., 2008). Each of these three elements must be represented through a schema and a JADE class implemented for each schema (from JADE interfaces). The ontology object (because it rarely changes during an agent's lifecycle) is implemented as a singleton object shared by all agents.

Concepts are the semantic elements of the vocabulary.

Table B-6 Ontology Concepts

Concept	Comments
Civilian	Civilian observed by a responder
Location	Location
Status	Safe, at risk, burn state
Population	Population observed by a responder
Civilians	Number of civilians observed
Victims	Number of victims observed
Fire	Observed fire
Location	Location
Nature	Ordinary, chemical, explosion, …
Scope	Size (X, Y)
Evolution	Speed of growth
GRIP	GRIP level of the incident
Level	Value between 0 and 5
Element	Observed physical element in the scenario (e.g. House)
Location	Location
Extension	Size (X, Y)
Access	Can it be accessed / crossed?
Condition	Burn state
Location	Defined location
Type	Brief description of location
Position	X, Y
Size	X, Y
Responder	Information about a responder (proxy)
Type	Rank, role and discipline
Location	Last known location
Status	Available, Requested, Committed
Strategy	Response strategy
Priorities	Assignment of firemen between fire fighting and rescue
Treatment protocol	Determines victim collection point
Exit criteria	Exit criteria per discipline
Time	Time attached to an observation
Timestamp	Timestamp of the observation

Predicates are the structural elements (defined over parameters as a link between them creates a predicate that can be true or false). The only predicate in the ontology is (Situation) **Awareness**, which groups an assertion on the concepts that constitute the *mental model* of the agent. An observation is a cyclical interaction between the agent and the world, but not directly part of its mental model. An agent observes the world and its observations become codified according to the ontology and stored in its *mental model*. In addition to individual situation awareness, shared situation awareness (from which the **Plan** action in the ontology is drawn up) is lead by an agent who can attach specific weights to communications from certain agents (e.g. giving more weight to higher ranking agents, using confirmation, taking into account time of message, etc.). In technical implementation terms, this means that the agent will have direct access to the world (the DES model) on an individual basis (observing, moving or changing the state of world objects by acting upon them). But to describe and communicate about the world, it will need the ontology, which is the language and the repository for its behavior and reasoning.

Table B-7 Ontology Predicates

Predicate	Comments
Awareness	Current Mental model of the incident per agent
Population	Estimated number of civilians and victims
Fire	Perceived fire
GRIP	GRIP level of the incident (0 to 5)
Elements	Known infrastructure and vehicles
Point of view	Point of view of observation
Responders	Known colleagues
Time	Timestamp of observation

Actions of the agents are special concepts that denote agent actions.

Table B-8 Ontology Actions

Action	Comments
Alarm	Alarm message
Type	Type of alarm
Destination	Location
Plan	Response plan per discipline
Strategy	Planned Strategy
Location	Defined operational and response locations
Responders	Responders requested per discipline
Resources	Material resources requested

B3. Activities Refinement Table

This step defines the activities refinement table, where application-dependent data, their structure and the algorithms that are going to be used by the agents are defined (Moraïtis & Spanoudakis, 2006). The activities refinement table is meant to specify the liveness properties of the agents, having defined the ontology. Under read and change, there is a reference to data classes (no longer world objects, but ontology-dependent classes). Under Description there is a top-level algorithm in pseudocode for the corresponding activity.

Table B-9 Activity refinement table

Role	Activity	Read	Change	Description

Fireman	Fireman	Responder
		Location
		Element
		Fire
		Civilian
			-	do GetToLocation
				do NotifyArrival
				while Strategy.exit != [exit criteria]
				  do AssessSituation
				  do InformAssessment
				  while fire != null || civlians.status != victim
				    do Respond
				    do UpdateAssessment
				    do InformResult
				  end while
				end while

Fireman	Respond		Fire
			Civilian
				if assigned Fire
				  do ContainFire
				else if assigned Victim
				  do MoveVictim
				end if

Medic	Medic	Responder
		Location
		Element
		Fire
			Civilian	do GetToLocation
				do NotifyArrival
				while Strategy.exit != [exit criteria]
				  do AssessSituation
				  do InformAssessment
				  while civlians.status != victim
				    do AssistVictim
				    do UpdateAssessment
				    do InformResult
				  end while
				end while

OvD	OvD	Grip	Plan	do GetToLocation
				while Grip > 0
				  do AnalyzeSituation
				  do EstablishCoPI
				  while Proposal not accepted
				    do PlanContainment
				  end while
				  do CommunicatePlan
				  do DeployContainment
				  do ReturnToCoPI
				end while

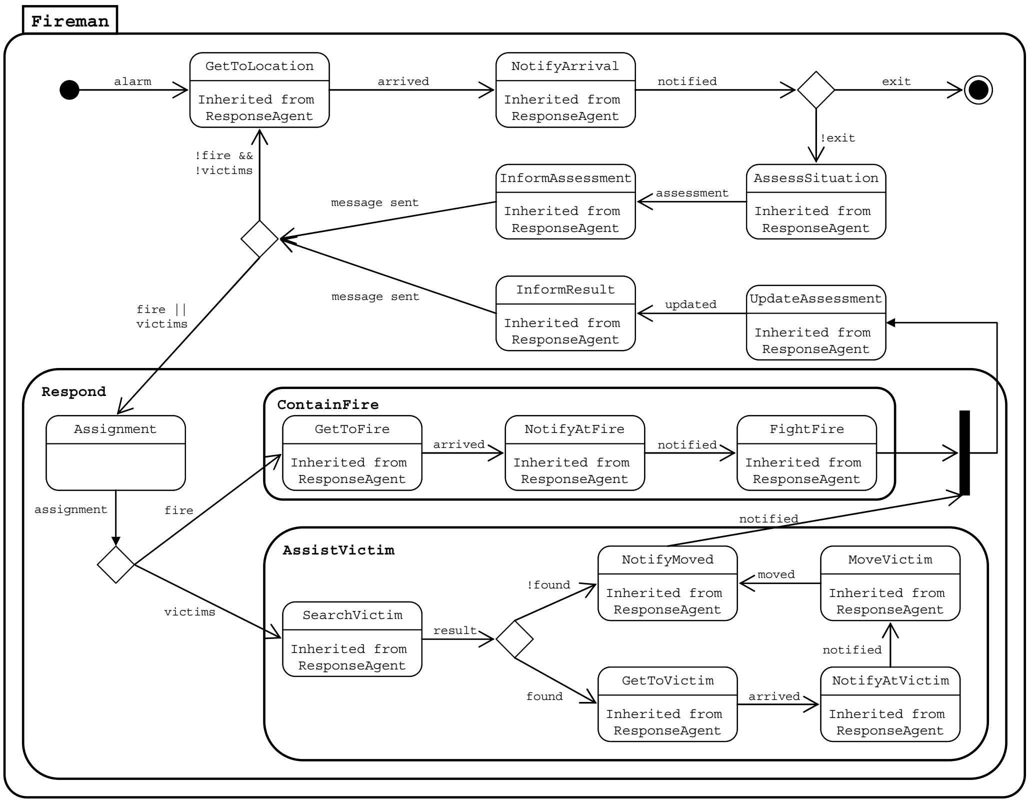
OvD	AnalyzeSituation	Plan (conditional)	Awareness	do RequestAssessment do MergeAssessments if Situation Awareness > 1st do InformPlanStatus end if do MutidisciplinaryConsultation
OvD	PlanContainmen t	Awareness	Strategy Location	do DetermineStrategy do DetermineLocations

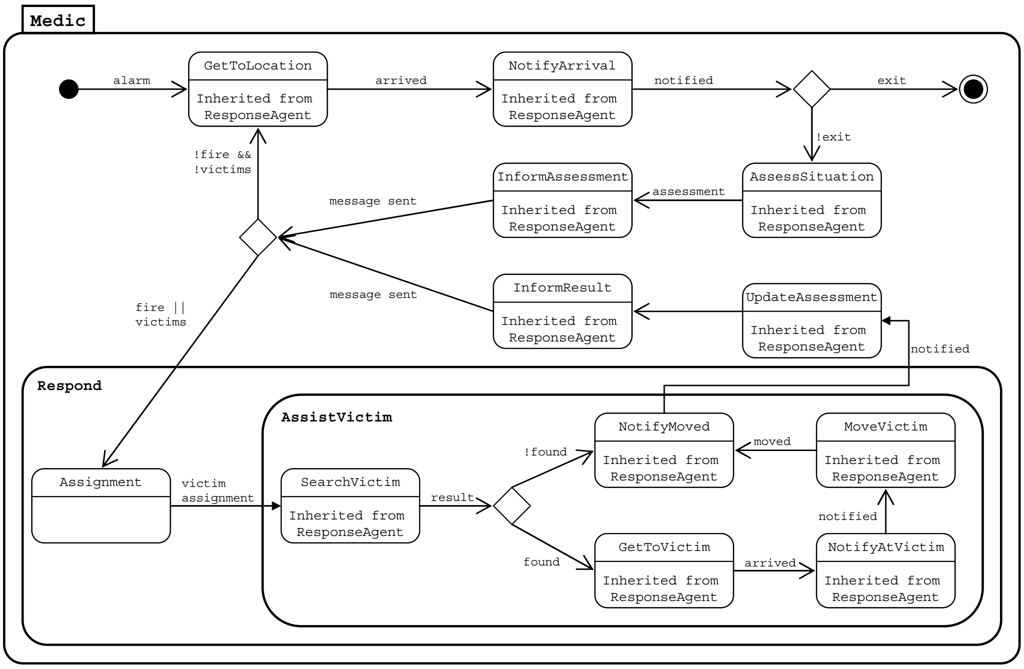
OvD	DeployContainm ent	Responder	Alarm	do GetToLoadingPost
				while Received units < Requested
				  do AlarmResponders
				  do DeployUnits
				end while

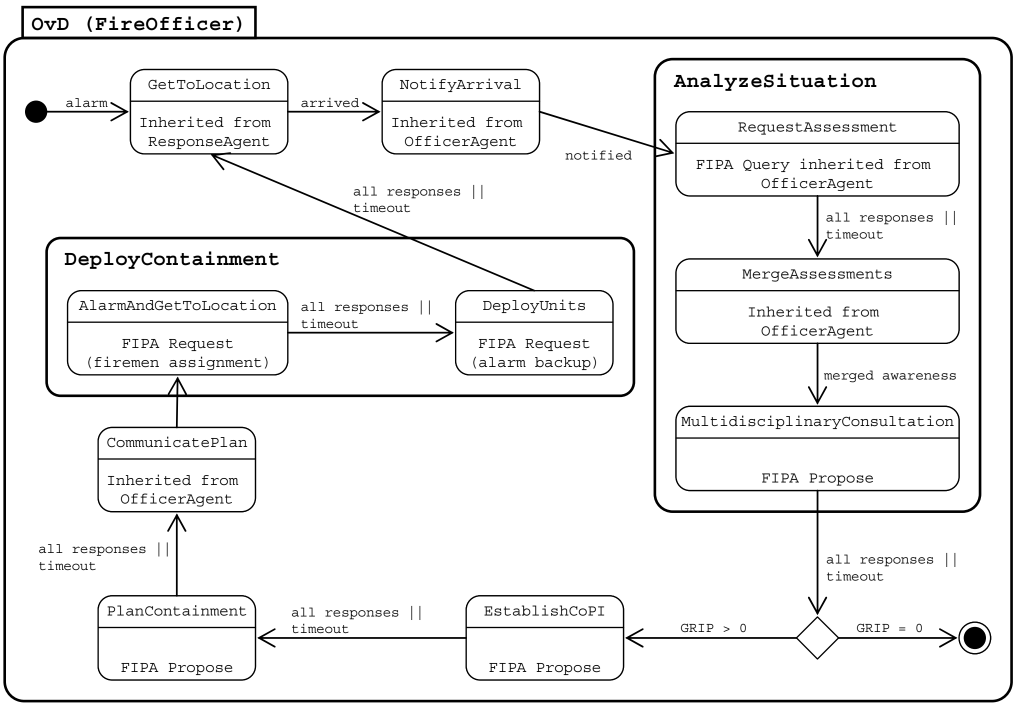
CL	CL	Grip
		Responder
			Awareness	while Grip > 0
				  while Proposals accepted < n
				    do NegotiateProposals
				  end while
				  do EvaluateResponse
				end while

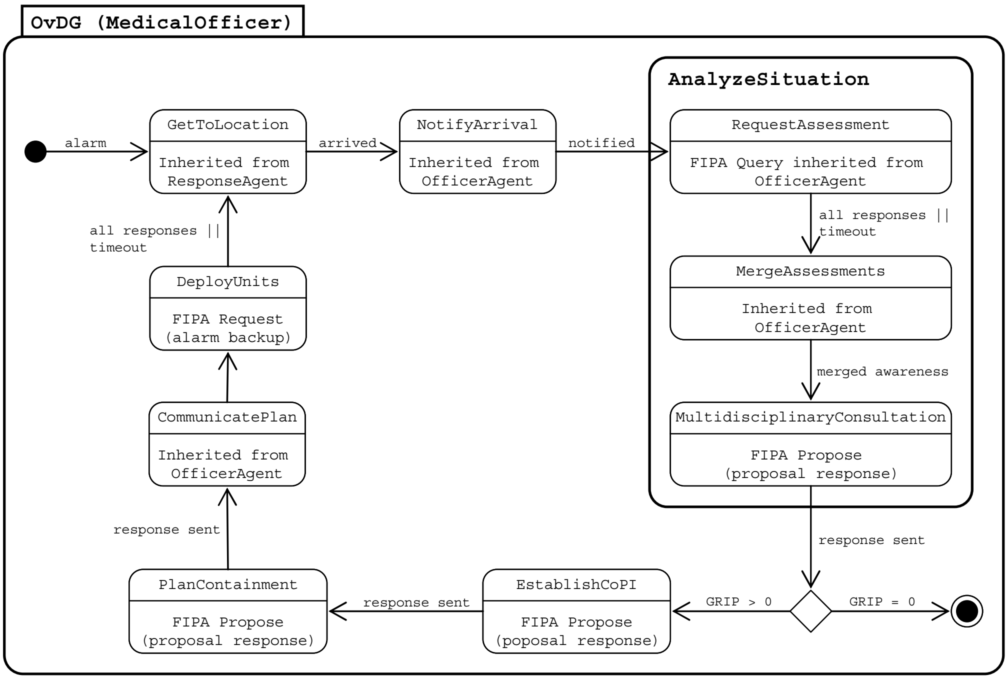
B4. Agent Behaviors

This step defines implements Gaia activities as Jade Behaviors (Moraïtis & Spanoudakis, 2006). First, behaviors are defined. Second, a state diagram (UML) is provided for each relevant behavior to help identify data exchange between behaviors and easily map to Jade FSM (Finite State Machine) behaviors. Implementation follows from the bottom-up (from simple to complex behaviors). Jade behaviors are defined from Gaia activities, through mapping activities (from section 2.4 and taking into account section 4.2.2). "All Gaia liveness formulas are translated to JADE behaviors. Activities and protocols can be translated to JADE behaviors, to action methods (which will be part of finite state machine - FSM like behaviors) or to simple methods of behaviors" (Moraïtis *et al.*, 2003). As a general rule, the "·" operator in a liveness formula denotes that the behavior at the left-hand side is complex, while the [], +, *, | operators denote that the left-hand side can be a finite state machine (Moraïtis & Spanoudakis, 2006). All behaviors should inherit from the `jade.core.behaviours.Behaviour` class.




Medic
alarm
GetToLocation
Inherited from ResponseAgent
arrived
NotifyArrival
Inherited from ResponseAgent
notified
exit
!exit
!fire && !victims
message sent
InformAssessment
Inherited from ResponseAgent
assessment
AssessSituation
Inherited from ResponseAgent
message sent
InformResult
Inherited from ResponseAgent
UpdateAssessment
Inherited from ResponseAgent
notified
fire || victims
Respond
AssistVictim
NotifyMoved
Inherited from ResponseAgent
moved
MoveVictim
Inherited from ResponseAgent
!found
Assignment
victim assignment
SearchVictim
Inherited from ResponseAgent
result
notified
found
GetToVictim
Inherited from ResponseAgent
arrived
NotifyAtVictim
Inherited from ResponseAgent


OvD (FireOfficer)
alarm
GetToLocation
Inherited from ResponseAgent
arrived
NotifyArrival
Inherited from OfficerAgent
notified
AnalyzeSituation
RequestAssessment
FIPA Query inherited from OfficerAgent
all responses || timeout
MergeAssessments
Inherited from OfficerAgent
merged awareness
MultidisciplinaryConsultation
FIPA Propose
all responses || timeout
DeployContainment
AlarmAndGetToLocation
FIPA Request (firemen assignment)
all responses || timeout
DeployUnits
FIPA Request (alarm backup)
CommunicatePlan
Inherited from OfficerAgent
all responses || timeout
PlanContainment
FIPA Propose
all responses || timeout
EstablishCoPI
FIPA Propose
GRIP > 0
GRIP = 0
all responses || timeout



OvDG (MedicalOfficer)
AnalyzeSituation
alarm
GetToLocation
Inherited from ResponseAgent
arrived
NotifyArrival
Inherited from OfficerAgent
notified
RequestAssessment
FIPA Query inherited from OfficerAgent
all responses || timeout
MergeAssessments
Inherited from OfficerAgent
merged awareness
MultidisciplinaryConsultation
FIPA Propose (proposal response)
response sent
GRIP > 0
GRIP = 0
EstablishCoPI
FIPA Propose (poposal response)
response sent
PlanContainment
FIPA Propose (proposal response)
response sent
CommunicatePlan
Inherited from OfficerAgent
DeployUnits
FIPA Request (alarm backup)
all responses || timeout

Appendix C. Expert Validation Questionnaire

Simulation assessment questionnaire

The following questionnaire is meant to measure your assessment of the simulation model from your observations of the animation and the experimental results.

Animation assessment

After having observed the animations, please state your level of agreement with the following statements.

1. The animations provide a "birds perspective" of the simulated emergency and its response.

O Strongly disagree / O Disagree / O Neither agree nor disagree / O Agree / O Strongly agree

2. The animations show the global effect of changing the initial number of civilians.

O Strongly disagree / O Disagree / O Neither agree nor disagree / O Agree / O Strongly agree

3. The animations show the global effect of changing the initial number of firemen.

O Strongly disagree / O Disagree / O Neither agree nor disagree / O Agree / O Strongly agree

4. The animations show the global effect of changing the initial number of medics.

O Strongly disagree / O Disagree / O Neither agree nor disagree / O Agree / O Strongly agree

5. The animations show the global effect of changing the coordination mechanisms between emergency responders.

O Strongly disagree / O Disagree / O Neither agree nor disagree / O Agree / O Strongly agree

6. The animations present an appropriate level of detail.

O Strongly disagree / O Disagree / O Neither agree nor disagree / O Agree / O Strongly agree

7. The animations display relevant dynamics in an easily detectable fashion.

O Strongly disagree / O Disagree / O Neither agree nor disagree / O Agree / O Strongly agree

Experimental results assessment

After having observed the experimental results, please state your level of agreement with the following statements.

8. The average response times are plausible for the kind of emergency simulated.

O Strongly disagree / O Disagree / O Neither agree nor disagree / O Agree / O Strongly agree

9. The average number of messages exchanged is plausible for the kind of emergency simulated.

O Strongly disagree / O Disagree / O Neither agree nor disagree / O Agree / O Strongly agree

10. The average number of victims is plausible for the kind of emergency being simulated.

O Strongly disagree / O Disagree / O Neither agree nor disagree / O Agree / O Strongly agree

11. The average number of fatalities is plausible for the kind of emergency being simulated.

O Strongly disagree / O Disagree / O Neither agree nor disagree / O Agree / O Strongly agree

12. The results (response time, messages, victims and fatalities) show the global effect of changing the coordination mechanisms between emergency responders.

O Strongly disagree / O Disagree / O Neither agree nor disagree / O Agree / O Strongly agree

Interview questions

13. In your opinion, is the simulation model potentially useful for planning coordination strategies for crisis response in advance? What do you think is missing to improve this potential usefulness?

14. In your opinion, is the simulation model potentially useful for training crisis responders and leaders on the effects of different coordination strategies? What do you think is missing to improve this potential usefulness?

15. In your opinion, could the simulation model be used for assessing technological tools that support coordination, prior to testing them in the field?

16. In your opinion, does the simulation model enable an improved understanding of coordination strategies for crisis response? Could it be used to discuss divergent views on how to coordinate during a crisis?

17. In your opinion, could the simulation model be used to gain additional insight on the relationship between top-down and bottom-up coordination during a crisis? Do you have an example of such insight?

Appendix D. Regression Analysis Tables

RT main effects models using original coding of A and R (mediation as base category)																
Model summary					ANOVA						Coefficients					
Model	R	R^2	Adjusted R^2	St. Error of the Estimate		Sum of squares	df	Mean Square	F	Sig.	Factor	B	Std. Error	Standardized Coefficient	t	Sig.
1	.835	.697	.692	18.55802	Regression	248447.043	5	49689.409	144.278	.000	(Const)	145.238	5.682		25.560	.000
					Residual	108141.610	314	344.400			C	.327	.041	.245	7.872	.000
					Total	356588.653	319				F	-3.144	.207	-.471	-15.152	.000
											M	-.876	.415	-.066	-2.110	.036
											R	42.783	2.075	.641	20.620	.000
											A	-.967	2.075	-.014	-.466	.641
2	.835	.697	.693	18.53495	Regression	248372.200	4	62093.050	180.742	.000	(Const)	144.755	5.580		25.943	.000
					Residual	108216.453	315	343.544			C	.327	.041	.245	7.882	.000
					Total	356588.653	319				F	-3.144	.207	-.471	-15.171	.000
											M	-.876	.414	-.066	-2.113	.035
											R	42.783	2.072	.641	20.645	.000

RT main effects models using alternate coding of A and R (autonomy as base category)																
Model summary					ANOVA						Coefficients					
Model	*R*	R^2	Adjusted R^2	St. Error of the Estimate		Sum of squares	df	Mean Square	*F*	Sig.	Factor	B	Std. Error	Standardized Coefficient	t	Sig.
1	.835	.697	.692	18.55802	Regression	248447.043	5	49689.409	144.278	.000	(Const)	187.054	5.682		32.919	.000
					Residual	108141.610	314	344.400			C	.327	.041	.245	7.872	.000
					Total	356588.653	319				F	-3.144	.207	-.471	-15.152	.000
											M	-.876	.415	-.066	-2.110	.036
											R	-42.783	2.075	-.641	-20.620	.000
											A	.967	2.075	.014	.466	.641
2	.835	.697	.693	18.53495	Regression	248372.200	4	62093.050	180.742	.000	(Const)	187.538	5.580		33.610	.000
					Residual	108216.453	315	343.544			C	.327	.041	.245	7.882	.000
					Total	356588.653	319				F	-3.144	.207	-.471	-15.171	.000
											M	-.876	.414	-.066	-2.113	.035
											R	-42.783	2.072	-.641	-20.645	.000

RT main effects models augmented with interaction effects																
Model summary					ANOVA						Coefficients					
Model	*R*	R^2	Adjusted R^2	St. Error of the Estimate		Sum of squares	df	Mean Square	*F*	Sig.	Factor	B	Std. Error	Standardized Coefficient	t	Sig.
1	.873	.763	.755	16.54988	Regression	271953.975	10	27195.397	99.290	.000	(Const)	139.874	15.998		8.743	.000
					Residual	84634.679	309	273.899			C	.617	.165	.462	3.727	.000
					Total	356588.653	319				F	-.868	.827	-.130	-1.048	.295
											M	-4.854	1.655	-.364	-2.933	.004
											R	10.185	9.791	.153	1.040	.299
											C*F	-.042	.007	-.688	-5.699	.000
											C*M	.014	.015	.111	.915	.361
											C*R	.482	.074	.599	6.512	.000
											M*F	.166	.074	.271	2.240	.026
											F*R	-.712	.370	-.177	-1.925	.055
											M*R	.951	.740	.118	1.285	.200
2	.873	.762	.755	16.54555	Regression	271724.545	9	30191.616	110.287	.000	(Const)	132.254	13.656		9.684	.000
					Residual	84864.109	310	273.755			C	.718	.123	.538	5.854	.000
					Total	356588.653	319				F	-.868	.827	-.130	-1.049	.295
											M	-3.838	1.227	-.287	-3.128	.002
											R	10.185	9.788	.153	1.040	.299
											C*F	-.042	.007	-.688	-5.700	.000
											C*R	.482	.074	.599	6.514	.000
											M*F	.166	.074	.271	2.241	.026
											F*R	-.712	.370	-.177	-1.925	.055
											M*R	.951	.740	.118	1.285	.200

RT main effects models augmented with interaction effects (continued)																
Model	R	R^2	Adjusted R^2	St. Error of the Estimate		Sum of squares	df	Mean Square	F	Sig.	Factor	B	Std. Error	Standardized Coefficient	t	Sig.
3	.872	.761	.755	16.54775	Regression	271428.171	8	33928.521	123.905	.000	(Const)	137.346	12.751		10.771	.000
					Residual	85160.482	311	273.828			C	.697	.121	.522	5.761	.000
					Total	356588.653	319				F	-.977	.821	-.146	-1.190	.235
											M	-4.056	1.209	-.304	-3.355	.001
											C*F	-.042	.007	-.688	-5.700	.000
											C*R	.526	.061	.653	8.623	.000
											M*F	.166	.074	.271	2.240	.026
											F*R	-.494	.305	-.123	-1.621	.106
											M*R	1.388	.610	.172	2.276	.024
4	.872	.760	.755	16.55879	Regression	271040.323	7	38720.046	141.214	.000	(Const)	123.200	4.619		26.674	.000
					Residual	85548.330	312	274.193			C	.783	.097	.586	8.076	.000
					Total	356588.653	319				M	-3.195	.969	-.239	-3.296	.001
											C*F	-.048	.005	-.786	-8.824	.000
											C*R	.532	.061	.661	8.755	.000
											M*F	.106	.055	.173	1.947	.052
											F*R	-.561	.300	-.139	-1.873	.062
											M*R	1.451	.608	.180	2.389	.018

NF main effects models using original coding of A and R (mediation as base category)																
Model summary					ANOVA						Coefficients					
Model	*R*	R^2	Adjusted R^2	St. Error of the Estimate		Sum of squares	df	Mean Square	*F*	Sig.	Factor	B	Std. Error	Standardized Coefficient	t	Sig.
1	.703	.495	.487	2.685	Regression	2210.454	5	442.091	61.332	.000	(Const)	5.151	.822		6.265	.000
					Residual	2256.154	313	7.208			C	.052	.006	.345	8.582	.000
					Total	4466.608	318				F	-.396	.030	-.528	-13.156	.000
											M	-.084	.060	-.056	-1.396	.164
											R	2.318	.301	.310	7.709	.000
											A	.045	.301	.006	.149	.882
2	.703	.495	.488	2.681	Regression	2210.294	4	552.573	76.899	.000	(Const)	5.173	.807		6.407	.000
					Residual	2256.314	314	7.186			C	.052	.006	.345	8.596	.000
					Total	4466.608	318				F	-.396	.030	-.529	-13.177	.000
											M	-.084	.060	-.056	-1.398	.163
											R	2.318	.300	.310	7.722	.000
3	.701	.492	.487	2.685	Regression	2196.250	3	732.083	101.573	.000	(Const)	4.544	.671		6.770	.000
					Residual	2270.358	315	7.207			C	.052	.006	.345	8.588	.000
					Total	4466.608	318				F	-.396	.030	-.529	-13.161	.000
											R	2.319	.301	.310	7.714	.000

NF main effects models using alternate coding of A and R (autonomy as base category)																
Model summary					ANOVA						Coefficients					
Model	R	R^2	Adjusted R^2	St. Error of the Estimate		Sum of squares	df	Mean Square	F	Sig.	Factor	B	Std. Error	Standardized Coefficient	t	Sig.
1	.703	.495	.487	2.685	Regression	2210.454	5	442.091	61.332	.000	(Const)	7.514	.822		9.138	.000
					Residual	2256.154	313	7.208			C	.052	.006	.345	8.582	.000
					Total	4466.608	318				F	-.396	.030	-.528	-13.156	.000
											M	-.084	.060	-.056	-1.396	.164
											R	-2.318	.301	-.310	-7.709	.000
											A	-.045	.301	-.006	-.149	.882
2	.703	.495	.488	2.681	Regression	2210.294	4	552.573	76.899	.000	(Const)	7.491	.807		9.282	.000
					Residual	2256.314	314	7.186			C	.052	.006	.345	8.596	.000
					Total	4466.608	318				F	-.396	.030	-.529	-13.177	.000
											M	-.084	.060	-.056	-1.398	.163
											R	-2.318	.300	-.310	-7.722	.000
3	.701	.492	.487	2.685	Regression	2196.250	3	732.083	101.573	.000	(Const)	6.863	.671		10.222	.000
					Residual	2270.358	315	7.207			C	.052	.006	.345	8.588	.000
					Total	4466.608	318				F	-.396	.030	-.529	-13.161	.000
											R	-2.319	.301	-.310	-7.714	.000

NF main effects models augmented with interaction effects																
Model summary					ANOVA						Coefficients					
Model	*R*	R^2	Adjusted R^2	St. Error of the Estimate		Sum of squares	df	Mean Square	*F*	Sig.	Factor	B	Std. Error	Standardized Coefficient	t	Sig.
1	.780	.608	.596	2.383	Regression	2717.635	10	271.764	47.858	.000	(Const)	-1.277	2.304		-.554	.580
					Residual	1748.973	308	5.678			C	.149	.024	.994	6.242	.000
					Total	4466.608	318				F	.095	.119	.127	.794	.428
											M	-.178	.238	-.119	-.745	.457
											R	.221	1.410	.030	.157	.875
											C*F	-.008	.001	-1.131	-7.268	.000
											C*M	-.001	.002	-.093	-.602	.548
											C*R	.058	.011	.642	5.441	.000
											M*F	.017	.011	.254	1.632	.104
											F*R	-.080	.053	-.178	-1.506	.133
											M*R	-.139	.107	-.154	-1.304	.193
2	.780	.608	.597	2.379	Regression	2717.495	9	301.944	53.342	.000	(Const)	-1.167	2.191		-.533	.595
					Residual	1749.113	309	5.661			C	.148	.024	.991	6.283	.000
					Total	4466.608	318				F	.093	.118	.124	.782	.435
											M	-.182	.236	-.122	-.772	.441
											C*F	-.008	.001	-1.131	-7.279	.000
											C*M	-.001	.002	-.093	-.603	.547
											C*R	.059	.009	.653	6.725	.000
											M*F	.017	.011	.254	1.635	.103
											F*R	-.076	.044	-.168	-1.720	.086
											M*R	-.130	.088	-.143	-1.478	.140

NF main effects models augmented with interaction effects																
Model	*R*	R^2	Adjusted R^2	St. Error of the Estimate		Sum of squares	df	Mean Square	*F*	Sig.	Factor	B	Std. Error	Standardized Coefficient	t	Sig.
3	.780	.608	.598	2.377	Regression	2715.440	8	339.430	60.087	.000	(Const)	-.450	1.838		-.245	.807
					Residual	1751.168	310	5.649			C	.139	.017	.927	7.973	.000
					Total	4466.608	318				F	.093	.118	.124	.785	.433
											M	-.278	.174	-.186	-1.600	.111
											C*F	-.008	.001	-1.132	-7.289	.000
											C*R	.059	.009	.653	6.733	.000
											M*F	.017	.011	.254	1.634	.103
											F*R	-.076	.044	-.168	-1.725	.086
											M*R	-.130	.088	-.143	-1.478	.140
4	.779	.607	.598	2.375	Regression	2711.955	7	387.422	68.668	.000	(Const)	.896	.663		1.353	.177
					Residual	1754.653	311	5.642			C	.130	.014	.872	9.385	.000
					Total	4466.608	318				M	-.360	.139	-.241	-2.591	.010
											C*F	-.007	.001	-1.049	-9.193	.000
											C*R	.058	.009	.646	6.694	.000
											M*F	.023	.008	.336	2.948	.003
											F*R	-.069	.043	-.154	-1.605	.109
											M*R	-.136	.087	-.150	-1.557	.120
5	.777	.604	.596	2.381	Regression	2698.270	6	449.712	79.346	.000	(Const)	1.130	.647		1.746	.082
					Residual	1768.338	312	5.668			C	.132	.014	.884	9.528	.000
					Total	4466.608	318				M	-.443	.129	-.296	-3.436	.001
											C*F	-.007	.001	-1.035	-9.076	.000
											C*R	.052	.008	.573	6.767	.000
											M*F	.024	.008	.351	3.077	.002
											F*R	-.101	.038	-.223	-2.638	.009

CC main effects models using original coding of A and R (mediation as base category)																
Model summary					ANOVA						Coefficients					
Model	*R*	R^2	Adjusted R^2	St. Error of the Estimate		Sum of squares	df	Mean Square	*F*	Sig.	Factor	B	Std. Error	Standardized Coefficient	t	Sig.
1	.733	.538	.530	194.133	Regression	1.376E7	5	2751202.6	73.000	.000	(Const)	190.275	59.441		3.201	.002
					Residual	1.183E7	314	37687.507			C	3.239	.434	.286	7.461	.000
					Total	2.559E7	319				F	-1.974	2.170	-.035	-.909	.364
											M	25.103	4.341	.222	5.783	.000
											R	350.875	21.705	.620	16.166	.000
											A	-80.438	21.705	-.142	-3.706	.000
2	.732	.536	.530	194.079	Regression	1.372E7	4	3431211.9	91.094	.000	(Const)	160.669	49.718		3.232	.001
					Residual	1.187E7	315	37666.803			C	3.239	.434	.286	7.463	.000
					Total	2.559E7	319				M	25.103	4.340	.222	5.784	.000
											R	350.875	21.699	.620	16.170	.000
											A	-80.438	21.699	-.142	-3.707	.000

CC main effects models using alternate coding of A and R (autonomy as base category)																
Model summary					ANOVA						Coefficients					
Model	R	R^2	Adjusted R^2	St. Error of the Estimate		Sum of squares	df	Mean Square	F	Sig.	Factor	B	Std. Error	Standardized Coefficient	t	Sig.
1	.733	.538	.530	194.133	Regression	1.376E7	5	2751202.6	73.000	.000	(Const)	460.713	59.441		7.751	.000
					Residual	1.183E7	314	37687.507			C	3.239	.434	.286	7.461	.000
					Total	2.559E7	319				F	-1.974	2.170	-.035	-.909	.364
											M	25.103	4.341	.222	5.783	.000
											R	-350.875	21.705	-.620	-16.166	.000
											A	80.438	21.705	.142	3.706	.000
2	.732	.536	.530	194.079	Regression	1.372E7	4	3431211.9	91.094	.000	(Const)	431.106	49.718		8.671	.000
					Residual	1.187E7	315	37666.803			C	3.239	.434	.286	7.463	.000
					Total	2.559E7	319				M	25.103	4.340	.222	5.784	.000
											R	-350.875	21.699	-.620	-16.170	.000
											A	80.438	21.699	.142	3.707	.000

CC main effects models augmented with interaction effects																
Model summary					ANOVA						Coefficients					
Model	R	R^2	Adjusted R^2	St. Error of the Estimate		Sum of squares	df	Mean Square	F	Sig.	Factor	B	Std. Error	Standardized Coefficient	t	Sig.
1	.859	.737	.724	148.711	Regression	1.887E7	15	1257798.9	56.876	.000	(Const)	41.850	150.55		.278	.781
					Residual	6722906.60	304	22114.824			C	3.449	1.524	.305	2.263	.024
					Total	2.559E7	319				F	22.540	7.619	.399	2.958	.003
											R	-330.425	89.536	-.584	-3.690	.000
											C*F	-.223	.067	-.429	-3.350	.001
											C*R	4.453	.665	.653	6.696	.000
											F*R	15.857	3.325	.465	4.769	.000
											M	7.045	15.238	.062	.462	.644
											A	698.475	89.536	1.235	7.801	.000
											C*M	.177	.133	.170	1.328	.185
											C*A	-.839	.665	-.123	-1.262	.208
											M*F	.049	.665	.009	.074	.941
											F*A	-32.200	3.325	-.944	-9.683	.000
											M*R	26.905	6.651	.394	4.046	.000
											M*A	-18.750	6.651	-.275	-2.819	.005
											A*R	-184.725	33.253	-.283	-5.555	.000

CC main effects models augmented with interaction effects (continued)																
Model	*R*	R^2	Adjusted R^2	St. Error Estimate		Sum of squares	df	Mean Square	*F*	Sig.	Factor	B	Std. Error	Standardized Coefficient	t	Sig.
2	.859	.737	.725	148.468	Regression	1.887E7	14	1347633.1	61.137	.000	(Const)	36.338	130.43		.279	.781
					Residual	6723026.65	305	22042.710			C	3.449	1.521	.305	2.267	.024
					Total	2.559E7	319				F	22.907	5.750	.405	3.984	.000
											R	-330.425	89.389	-.584	-3.696	.000
											C*F	-.223	.066	-.429	-3.356	.001
											C*R	4.453	.664	.653	6.707	.000
											F*R	15.857	3.320	.465	4.777	.000
											M	7.780	11.500	.069	.677	.499
											A	698.475	89.389	1.235	7.814	.000
											C*M	.177	.133	.170	1.330	.185
											C*A	-.839	.664	-.123	-1.264	.207
											F*A	-32.200	3.320	-.944	-9.699	.000
											M*R	26.905	6.640	.394	4.052	.000
											M*A	-18.750	6.640	-.275	-2.824	.005
											A*R	-184.725	33.198	-.283	-5.564	.000

CC main effects models augmented with interaction effects (continued)																
Model	R	R^2	Adjusted R^2	St. Error Estimate		Sum of squares	df	Mean Square	F	Sig.	Factor	B	Std. Error	Standardized Coefficient	t	Sig.
3	.858	.737	.726	148.336	Regression	1.886E7	13	1450521.2	65.922	.000	(Const)	94.688	97.764		.969	.334
					Residual	6733114.71	306	22003.643			C	2.865	1.252	.253	2.289	.023
					Total	2.559E7	319				F	22.907	5.745	.405	3.987	.000
											R	-340.150	88.148	-.601	-3.859	.000
											C*F	-.223	.066	-.429	-3.359	.001
											C*R	4.453	.663	.653	6.713	.000
											F*R	15.857	3.317	.465	4.781	.000
											A	688.750	88.148	1.218	7.814	.000
											C*M	.254	.066	.245	3.835	.000
											C*A	-.839	.663	-.123	-1.265	.207
											F*A	-32.200	3.317	-.944	-9.708	.000
											M*R	28.202	6.351	.413	4.440	.000
											M*A	-17.453	6.351	-.256	-2.748	.006
											A*R	-184.725	33.169	-.283	-5.569	.000
4	.858	.736	.725	148.481	Regression	1.882E7	12	1568464.9	71.143	.000	(Const)	126.150	94.638		1.333	.184
					Residual	6768310.76	307	22046.615			C	2.446	1.209	.216	2.024	.044
					Total	2.559E7	319				F	22.907	5.751	.405	3.983	.000
											R	-340.150	88.234	-.601	-3.855	.000
											C*F	-.223	.066	-.429	-3.355	.001
											C*R	4.453	.664	.653	6.707	.000
											F*R	15.857	3.320	.465	4.776	.000
											A	625.825	72.835	1.107	8.592	.000
											C*M	.254	.066	.245	3.831	.000
											F*A	-32.200	3.320	-.944	-9.698	.000
											M*R	28.202	6.358	.413	4.436	.000
											M*A	-17.453	6.358	-.256	-2.745	.006
											A*R	-184.725	33.201	-.283	-5.564	.000

Summary

Crisis response efforts often require coordinating a previously unknown adhocracy of agencies that unpredictably enter and exit a new situation under time pressure and high risk. While current technologies that support coordination are successful for well-defined static process descriptions, they may fall short in the face of more complex and dynamic scenarios, such as a crisis or emergency. The following research contributes a set of design artifacts that are used to gain insight into coordination in crisis response and its support with information and communication technology (ICT). A simulation model, together with the constructs, methods and design models that went into its development, was built for this purpose. The simulation model operationalizes constructs from the information-processing view of coordination in crisis response, using an agent-based representation that enables experimenting with both mediated coordination mechanisms as well as mutually adjusted coordination mechanisms for a crisis response organization in a specific crisis scenario. Experimenting with this simulation model provides theoretical insight about coordination and about the supporting role that ICT has.

Crisis response is critical for society in general, but more specifically for health authorities, fire departments, municipalities, large industrial complexes, or national security boards, among others. Such organizations are constantly facing the risk of a crisis for which they need to activate ad hoc networks of people or agencies to handle the situation. Large crises or disasters require leadership, intensive communication, coordination and immediate response to a changing environment, sometimes across regional or international borders. However, coordination continues to be a key problem in crisis response for which academic research is still scarce. Coordination challenges are endemic to a crisis, especially one of a multi-disciplinary nature, i.e. one that involves fire services, police, medical emergency teams and perhaps chemical or hazmat experts and volunteer organizations, among others. Such coordination challenges include: heterogeneity (of information and participants), lack of information quality, information overload, and uncertainty. In addition, there is a need for adaptation and improvisation, set against a command and control structure under time pressure and often with insufficient resources. To contribute to dealing with these challenges, ICT can be used to support crisis response coordination. Some examples of ICT for crisis response include: workflow technology, agent technology, decision support systems, information management systems, geographic information technology, knowledge management systems, simulation and gaming, and integrated systems. However, there is a gap between the possibilities that ICT offers and the support it delivers. Existing tools are sometimes not used and new (mostly web-based or wireless) ICT is emerging.

This problem situation leads to research questions. (1) How can the current understanding of coordination in crisis response be extended to account for emergent coordination? (2) How does coordination based on centralized command and control compare to decentralized or emergent coordination in crisis response? (3) How does an extended understanding of coordination in crisis response and of its alternative configurations contribute to bridging the gap

between the possibilities and realities of ICT support during a crisis? The research approach used to answer these questions follows a design science research strategy with three cycles: a relevance cycle (using case studies), a rigor cycle (exploring the theoretical knowledge base) and a design cycle (using simulation). The results include an instantiated artifact and a theoretical contribution comprising constructs, methods and models.

Rigor cycle. Stemming from an information-processing (I-P) perspective, coordination can be defined as "managing dependencies between activities" (Malone & Crowston, 1994). In crisis response literature, many refer to coordination in terms of this definition or by using the information-processing view directly or indirectly in a variety of settings. The I-P view is related to coordination and based on bounded rationality. In this view, organizational design strategies include reducing I-P needs or increasing I-P capabilities.

Coordination mechanisms can be used to increase I-P capabilities to manage coordination dependencies. Such dependencies are classified into: flow, fit, and sharing. On the other hand, coordination mechanisms are classified into: standards, mediation, and mutual adjustment. While the I-P view emphasizes standards and hierarchy, in part due to Herbert Simon's notion of "near-decomposability", this is limited for crisis response. Alternatives and extensions to the I-P view include: collaborative coordination, behavioral theories, situated coordination, governance, role-based, and practice-based coordination. Moreover, while ICT can be used as a coordination mechanism to increase I-P capabilities, it can also increase coordination costs. ICT may increase the severity of a crisis or transform coordination problems into worse ones. Through new designs and institutional support the likelihood of ICT success can be increased. Simulation can be used for developing insight about such design and institutional support.

Relevance cycle. Crisis management is critical for large ports constantly exposed to threats. The Port of Rotterdam (PoR) responds with an operational coordination team and a command structure. In order to exercise both capabilities, the PoR periodically undergoes crisis response exercises, which become the setting for the two case studies contained in this thesis. The first case study focuses on first response and operational leadership, using observations of a set of training exercises, interviews and documents. Findings indicate wide ICT use, including: telecommunications, integrated systems, geographic information technology, and workflow simulation, together with non computer-based technology. By using the I-P view as analytical framework, other findings are classified into: flow dependencies, fit dependencies, and sharing dependencies. Discussion points of the case include: the relationship between emergence and mutual adjustment, the preference on mediation in practice, and examples of situated uses of ICT. The second case study departs from the claim that coordination is tied to information quality. In this case, data collection and analysis was based on three categories: coordination challenges, information management activities, and information quality attributes (accuracy, timeliness, relevance, quantity, completeness, format, security, and consistency). Findings of the case illustrate how coordination challenges can be tackled by using information management services that support information quality.

Rigor cycle. The presence of emergence in crises (e.g. emergent coordination, emergent response groups and emergent uses of ICT) results in changing perspective with regards to coordination. Accordingly, complex adaptive systems (CAS) have been adopted as a new theoretical lens with for crisis response. A CAS-based study of emergence shows that is open to multiple definitions, including: weak (nominal) emergence, pattern emergence, strong emergence, and synchronic or diachronic emergence. Emergence can be simulated with agents organized in a multi-agent system (MAS), which is also ideal for studying coordination. Emergent coordination in MAS can be compared to other (top-down) mechanisms based on their characteristics or through simulation. Agent-based simulations of emergent phenomena include: emergence of coordination, and emergent properties of coordination, with or without communication. They can also be used to compare coordination mechanisms in crisis response.

Design cycle. The design cycle starts with the development of a simulation model using agents and discrete-event simulation. The simulation method employed is aimed at theory development and design instantiation by following a set of activities: determine research question (those posed earlier); identify extant theory (the I-P view extended with notions from CAS and MAS); conceptualization; model construction; verification and validation; metamodeling; and experimenting. Conceptualization is supported by the GAIA MAS design method. Model construction (translation into a computer-readable model) transforms the GAIA-based analysis and design into an implementation-dependent model with JADE as the underlying agent platform. The simulation approach combines agent-based and discrete-event modeling.

Verification and validation of the resulting simulation model is done by transparently documenting the design artifacts and the software code, in addition to performing sensitivity analysis and expert validation. Expert validation was done through animation assessment and output assessment. An on-line evaluation using academics and practitioners was complemented with an interview. Results from the animation assessment and the output assessment support the model's ability to produce plausible effects using different coordination mechanisms. The interview addressed the model use for planning, for training, for ICT assessment, for improved understanding, and for gaining insight. Evaluation results also provide requirements for new design cycles.

Metamodeling is achieved through design of experiments (DoE), which starts with potential factors for the incident, for the civilians, for the responders, for the infrastructure, and for the coordination mechanisms. Five factors are selected along with outputs related to response effectiveness and coordination cost. A polynomial regression model was obtained through a full factorial experimental design. The metamodels specify the main effects on response time, on fatalities and on coordination cost, all augmented with interaction effects. They are then used to run refined, simplified, and faster experiments to obtain additional insight.

With respect to the first research question this research found that emergence can be understood as a central property of (agent-based) dynamic systems which results from confronting the agents within a specific structure of interaction constitutive of both the agent and system levels. In relation to the I-P view, this led to the recognition of mutual adjustment as representing coordination in practice, while also being embedded within an organizational structure that includes standards and mediation. The interaction of the I-P view with agents and emergence resulted in the following insight. Since a crisis is defined by uncertainty, from an information-processing view this suggests that mutual adjustment should be the dominant coordination mechanism. Nonetheless, the presence and support for hierarchical organizations and plans in practice still emphasizes standards and mediation. But there is an increasing recognition that this can result in poor results. The decision to use agent-based simulation is a recognition that decentralized, mutually adjusted coordination should be understood and supported, instead of neglected, while at the same time providing a testbed to compare mutually adjusted mediation to centralization in specific crisis conditions, under the recognition that both will be present. Coordination mechanisms in crisis response should thus not be treated as mutually exclusive, but as mutually related, which favors the use of agent-based simulation to evaluate, compare and gain insight into their effects and interactions.

The second research question asked about precisely this comparison between centralized coordination (stemming from command-and-control approaches to crisis response) and decentralized coordination (stemming from emergent or net-centric approaches to crisis response). We obtained insight into this question by performing metamodeling and experiments with the simulation model. This insight is limited by the domain set out in the design of experiments and includes: (1) In terms of response time and number of fatalities, there is no significant difference in coordinating assignment of firemen between fire fighting and rescue regardless of whether the coordination mechanism is mediated or autonomous. (2) The interaction between assignment coordination and rescue coordination indicates that one coordination mechanism can influence the performance of another. This suggests that emergence of coordination is a result of the interaction of all coordination mechanisms employed during crisis response. (3) The configuration of coordination mechanisms which is capable of reducing coordination cost the most is mediated rescue and autonomous assignment.

The third question asked about bridging the gap between the possibilities and realities of ICT support for coordination during a crisis. It was established that ICT can increase information-processing capabilities, but can also introduce new coordination costs. In the first case study it was shown how different ICT tools are used in the Port of Rotterdam for supporting crisis response and that these can support different coordination mechanisms and be used outside the expected standard manner. The second case study then made the argument that coordination can be improved through the inclusion of information management services that support information quality; hence, a shared data space (SDS) was selected for inclusion into the simulation, as a way to support coordination / information quality. The experiments with the metamodel provided the following insight regarding the use of the SDS to support coordination: When victim rescue is coordinated through the mediation of a shared data space, a significant reduction in response time and fatalities can be obtained, as compared to autonomous coordination of rescue. If victim rescue is coordinated through the mediation of a shared data space, the individual contribution of rescuers to reduction of response time and fatalities is significant up to a higher number of responders, when compared to autonomous coordination of rescue.

Samenvatting

Crisisrespons vereist vaak de coördinatie van een eerder niet-bestaande adhocratie van agentschappen die op onvoorspelbare wijze een nieuwe tijdskritische en risicovolle situatie in- en uitstappen. Hoewel huidige technologieën, die coördinatie ondersteunen, succesvol zijn bij goed gedefinieerde statische beschrijvingen van processen, schieten ze tekort ten opzichte van meer complexe en dynamische scenario's, zoals noodgevallen en crisissen. De bijdrage van dit onderzoek bestaat uit een verzameling artefacten die inzicht verschaffen in de coördinatie van crisisrespons en de ondersteuning met informatie- en communicatietechnologie (ICT). Voor dit doel is een simulatiemodel ontwikkeld, samen met de constructies, methodes and ontwerpmodellen om het model te ontwikkelen. Het simulatiemodel operationaliseert de constructen van de coördinatie van crisisrespons vanuit een informatieverwerkingsperspectief, gebruikmakend van een *agent-based* representatie die experimenteren toelaat met zowel bemiddelde coördinatie, als onderling aangepaste coördinatiemechanismen voor crisisrespons organisaties in specifieke crisisscenario's. Het experimenteren met simulatiemodellen geeft theoretisch inzicht over coördinatie en de ondersteunende rol van ICT hierin.

Crisisrespons is van kritisch belang voor de maatschappij in het algemeen, en meer specifiek voor autoriteiten, brandweer, gemeentes, grote industriële installaties, of de raad voor nationale veiligheid. Zulke organisaties hebben continu te maken met het risico dat crisissen ontstaan waarvoor ze ad hoc netwerken van personen en agentschappen moeten opstellen om de situatie te handhaven. Grote crisissen of catastrofes vereisen leiderschap, intensieve communicatie, coördinatie en onmiddellijke reacties ten opzichte van veranderlijke omgevingen die soms regionale en zelfs nationale grenzen overschrijden. Crisissen zijn kenmerkend moeilijk te coördineren, vooral als ze een multidisciplinair karakter hebben, zoals wanneer er tegelijkertijd behoefte is aan brandweer, politie, medische urgentie teams, vrijwilligersorganisaties en zelfs experts op het gebied van chemische of gevaarlijke stoffen. De coördinatie hiervan bevat de volgende uitdagingen: heterogeniteit (van informatie en deelnemers), gebrekkige kwaliteit van informatie, information overload, en onzekerheden. Bovendien is er een behoefte aan aanpassing en improvisatie, tegen de achtergrond van een bevelsstructuur onder tijdsdruk en vaak met onvoldoende middelen. ICT kan ondersteuning bieden bij het coördineren van crisisrespons waarin deze moeilijkheden zich voordoen. Enkele ICT-voorbeelden bedoeld voor crisisrespons zijn: workflow technologie, *agent* technologie, beslissingsondersteunende systemen, systemen voor informatiebeheer, geografische informatiesystemen, kennisbeheerssystemen, simulaties en gaming, en geïntegreerde systemen. Er bestaat momenteel een discrepantie tussen de mogelijkheden die ICT biedt en de ondersteuning die ICT momenteel werkelijk levert. Bestaande hulpmiddelen worden vaak niet gebruikt terwijl er steeds meer nieuwe (vaak webgebaseerde of draadloze) ICT oplossingen verschijnen.

De probleemschets leidt tot de volgende onderzoeksvragen: (1) Hoe kan het huidig begrip van coördinatie in crisisrepons uitgebreid worden met emergente coördinatie? (2) Hoe kan coördinatie gebaseerd op een gecentraliseerde *command*

& control worden vergeleken met gedecentraliseerde of emergente coördinatie in crisisrespons? (3) Hoe kan een uitgebreid begrip van coördinatie in crisisrespons en bijhorende alternatieve configuraties bijdragen tot het overbruggen van het gat tussen de mogelijkheden en de realiteit van ICT-ondersteuning tijdens een crisis? De gebruikte onderzoeksaanpak beantwoordt deze vragen door middel van een *design science* strategie met drie cycli: een relevantiecyclus (gebruikmakend van case studies), een strengheidcyclus (verkennen van theoretische kennis), en een ontwerpcyclus (gebruikmakend van simulatie). Het resultaat hiervan is een artefact en een theoretische bijdrage bestaande uit constructies, methodes en modellen.

Strengheidcyclus. Vanuit een informatieverwerkingsperspectief (IV-perspectief) kan coördinatie gedefinieerd worden als het "beheren van afhankelijkheden tussen activiteiten" (Malone & Crowston, 1994). In literatuur met betrekking tot crisisrespons, wordt vaak verwezen naar coördinatie in termen van deze definitie of door direct of indirect gebruik te maken van het IV-perspectief in verschillende omstandigheden. Het IV-perspectief is gerelateerd tot coördinatie en gebaseerd op beperkt rationalisme. Vanuit dit perspectief behoort het verminderen van de nood voor informatieverwerking of het vergroten van IV-mogelijkheden tot de organisatorische ontwerpstrategieën.

Coördinatiemechanismen kunnen worden gebruikt om de IV-mogelijkheden te verbeteren om zo coördinatieafhankelijkheden te beheren. Dergelijke afhankelijkheden kunnen geclassificeerd worden als: *flow, fit,* en *sharing.* De coördinatiemechanismen kunnen worden geclassificeerd als: standaarden (*standards),* bemiddeling (*mediation),* en onderlinge aanpassing (*mutual adjustment).* Hoewel het IV-perspectief de nadruk legt op standaarden en hiërarchieën, deels dankzij Simon's notie van "*near-decomposability",* is dit gelimiteerd tot crisisrespons. Alternatieven en uitbreidingen op het IV-perspectief zijn onder andere: collaboratieve coördinatie, gedragstheorie, situationele coördinatie, *governance* en rol- en praktijkgebaseerde coördinatie. Verder kan ICT gebruikt worden als een coördinatiemechanisme om IV-mogelijkheden te verbeteren, maar kan het ook de kosten van coördinatie verhogen. ICT kan een crisis verergeren of de coördinatieproblemen verslechteren. Door nieuwe ontwerpen en institutionele ondersteuning kan de kans op succes met behulp van ICT worden vergroot. Simulatie kan gebruikt worden om inzicht te verschaffen over dergelijke ontwerpen en institutionele ondersteuning.

Relevantiecyclus. Crisisbeheer is essentieel voor grote havens die voortdurend risico's lopen. De Haven van Rotterdam beschikt over een operationeel coördinatieteam en een commandostructuur om risico's het hoofd te bieden. Voor het oefenen van deze taken houdt de Haven van Rotterdam regelmatig crisisresponsoefeningen, die hier gebruikt worden voor twee case study's. De eerste case study focust op eerste hulp en operationele leiderschap, en maakt gebruik van observaties op een trainingslocatie, interviews en documentatie. De uitkomsten van de case study tonen een wijdverbreid gebruik van ICT, zoals telecommunicatie, geïntegreerde systemen, geografische informatie systemen, en workflow simulaties, samen met niet-computer gebaseerde technologie. Door gebruik te maken van het IV-perspectief als een analytisch raamwerk, kunnen andere bevindingen geclassificeerd worden als: *flow* afhankelijkheden, *fit* afhankelijkheden, and *sharing* afhankelijkheden. Discussiepunten met betrekking tot deze case study zijn: de relaties tussen emergente en onderlinge aanpassingen, de voorkeur voor bemiddeling in de praktijk en voorbeelden van situationeel gebruik van ICT. De tweede case study heeft als vertrekpunt de stelling dat coördinatie gebonden is aan de kwaliteit van de informatie. In dit geval was dataverzameling en analyse gebaseerd op drie categorieën: uitdagingen met betrekking tot coördinatie; activiteiten met betrekking tot het beheer van informatie; en attributen met betrekking tot de kwaliteit van de informatie (accuraatheid, stiptheid, relevantie, kwantiteit, volledigheid, formaat, veiligheid en consistentie). Uitkomsten van deze case study tonen hoe uitdagingen met betrekking tot coördinatie kunnen worden benaderd door het gebruiken van informatiebeheerdiensten ter ondersteuning voor de kwaliteit van informatie.

Strengheidcyclus. De aanwezigheid van emergentie in crisissen (bijvoorbeeld emergente coördinatie, emergente responsgroepen en het emergent gebruik van ICT) resulteren in perspectiefveranderingen met betrekking tot coördinatie. Hiervoor wordt de theorie van complex adaptieve systemen (CAS) gebruikt om crisisrespons te bestuderen. Een CAS-gebaseerde studie van emergentie toont dat het open staat voor meerdere definities waaronder zwakke (nominale) emergentie, patroon emergentie, sterke emergentie en synchrone of diachrone emergentie. Emergentie kan worden gesimuleerd met agenten georganiseerd in een multi-agent systeem (MAS), wat ook uiterst geschikt is om coördinatie te bestuderen. Emergente coördinatie in MAS kan worden vergeleken met andere (top-down) mechanismen op basis van hun karakteristieken of door simulatie. Agentgebaseerde simulaties van emergente fenomenen zijn o.a. emergentie van coördinatie en emergente eigenschappen van coördinatie, met of zonder communicatie. Ze kunnen ook gebruikt worden om coördinatiemechanismen te vergelijken in crsisrespons.

Ontwerpcyclus. De ontwerpcyclus begint met het ontwikkelen van een simulatiemodel met behulp van agenten en *discrete-event* simulatie. De simulatiemethode die hier wordt gebruikt, is bedoeld voor het ontwikkelen van theorieën en het realiseren van ontwerpen, door het volgen van een verzameling van activiteiten: vaststellen van de onderzoeksvraag (deze is eerder gesteld); identificeer bestaande theorie (het IV-perspectief werd uitgebreid met de noties van CAS en MAS), conceptualisatie; construeren van een model; verificatie en validatie; metamodelleren en experimenteren. Conceptualisatie is ondersteund door de GAIA MAS ontwerpmethode. De constructie van het model (vertaling naar computerleesbare code) transformeert de GAIA-gebaseerde analyse en ontwerp naar een implementatieafhankelijk model voor JADE en het onderliggend agentplatform. De aanpak met behulp van simulatie combineert *agent based* en discete-event modelleren.

Verificatie en validatie van het resulterend simulatiemodel is uitgevoerd door middel van transparante documentatie van ontwerpartefact en software code. Verder zijn een gevoeligheidsanalyse en een expert-validatie uitgevoerd. De expert-validatie is uitgevoerd door middel van een evaluatie van de animatie en uitvoerdata. Hierbij is er ook een online evaluatie met academici en beoefenaars toegevoegd door middel van een interview. De resultaten van de evaluatie van de animatie en uitvoerdata ondersteunen het feit dat het model geloofwaardige effecten produceert met gebruik van verschillende coördinatiemechanismen. De interviews waren gericht op het gebruik van het model voor planning, training, ICT evaluatie, een verbeterd begrip en om inzicht te verschaffen. De resultaten van de evaluatie hebben geleid tot eisen voor nieuwe ontwerpcycli.

Metamodellen zijn ontwikkeld door middel van het ontwerpen van experimenten, die beginnen met potentiële factoren voor het ongeval, voor de burgers, voor de hulpverleners, voor de infrastructuur, en voor de coördinatiemechanismen. Vijf factoren werden geselecteerd samen met uitvoerdata gerelateerd aan de effectiviteiten van respons en coördinatiekosten. Een polynomiaal regressiemodel werd ontwikkeld door middel van een volledig factoriaal experimenteel ontwerp. De metamodellen specificeren de belangrijkste effecten voor responstijd, slachtoffers en coördinatiekosten, allen verrijkt met interactie-effecten. Hierna werden de metamodellen gebruikt om fijnere, versimpelde en snellere experimenten uit te voeren om zo extra inzichten te krijgen.

In antwoord op de eerste onderzoeksvraag, blijkt uit dit onderzoek dat emergentie kan worden begrepen als de centrale eigenschap van (*agent-based*) dynamische systemen die worden bereikt door *agents* tegenover een specifieke structuur van interacties te stellen die bestaat uit zowel *agents* als systeemniveaus. Met betrekking tot het IV-perspectief, leidt dit tot de erkenning van onderlinge aanpassing als toonbeeld van coördinatie in de praktijk, terwijl dit ook ingebed ligt in organisatorische structuren die standaarden en bemiddeling bevatten. De interactie van het IV-perspectief met *agents* en emergentie resulteert in de volgende inzichten: Omdat een crisis wordt gedefinieerd door onzekerheid, wordt vanuit een IV-perspectief gesteld dat onderlinge aanpassing het dominant coördinatiemechanisme zou moeten zijn. Niettemin zal de aanwezigheid en ondersteuning voor hiërarchische organisatie en plannen in de praktijk steeds nadruk leggen op standaarden en bemiddeling. Maar er is toenemende erkenning dat dit kan leiden tot slechte resultaten. De beslissing om *agent-based* simulatie te gebruiken, is een erkenning dat een gedecentraliseerde, onderling aangepaste coördinatie zou moeten worden begrepen en ondersteund, in plaats van genegeerd. Daarnaast kan dit ook een testbed verzorgen om onderlinge aangepaste bemiddeling en centralisatie te vergelijken in specifieke crisisrespons omstandigheden, in de veronderstelling dat beide aanwezig zullen zijn. Coördinatiemechanismen in crisisrespons zouden dus niet moeten worden behandeld als elkaar uitsluitend, maar als aan elkaar gerelateerd, waardoor een voorkeur ontstaat voor *agent-based* simulatie om te evalueren, te vergelijken en om het verkrijgen van inzicht in hun effecten en interacties.

De tweede onderzoeksvraag richtte zich op deze vergelijking tussen gecentraliseerde coördinatie (afkomstig van het beheer en beheers aanpakken) en gedecentraliseerde coördinatie (afkomstig van emergente of *net-centric* aanpakken tot crisisrespons). Door middel van metamodellen en experimenten met het simulatiemodel, hebben we inzicht verkregen in dit onderwerp. Dit inzicht is beperkt door het domein dat werd bepaald voor het ontwerp van experimenten en bevat: (1) In termen van responstijd en dodental is er geen significant verschil in de coördinatie van taken van brandweerlieden tussen brandblussen en reddingen ongeacht de keuze tussen autonome en bemiddelde coördinatiemechanismen. (2) De interactie tussen de coördinatie van taken en reddingscoördinatie duidt dat coördinatiemechanismen invloed kunnen uitoefenen op elkaars effectiviteit. Dit suggereert dat emergentie van coördinatie een resultaat is van de interactie tussen alle coördinatiemechanismen gebruikt tijdens een crisisrespons. (3) De configuratie van coördinatiemechanismen die over de mogelijkheid beschikken om coördinatiekosten het meest te verminderen, is bemiddelde redding met autonome takensplitsing.

De derde onderzoeksvraag richtte zich op de mogelijkheid om het gat te overbruggen tussen de mogelijkheden en werkelijkheden van ICT ondersteuning voor de coördinatie tijdens een crisisrespons. Er werd vastgesteld dat ICT informatieverwerkingsmogelijkheden kan verbeteren maar dat het ook nieuwe coördinatiekosten kan introduceren. In de eerste case study werd getoond hoe verschillende ICT hulpmiddelen worden gebruikt in de Haven van Rotterdam om crisisrespons te ondersteunen en dat deze verschillende coördinatiemechanismen kunnen ondersteunen en ook gebruikt kunnen worden buiten de verwachte standaardmanier. De tweede case study gaf aan dat coördinatie verbeterd kan worden door het introduceren van informatiebeheerdiensten die de kwaliteit van informatie ondersteunen. Daarom werd een *shared data space* (SDS) geselecteerd om in de simulatie te worden gebruikt, zodat deze de coördinatie en kwaliteit van informatie kan ondersteunen. De experimenten met het metamodel gaven de volgende inzichten met betrekking tot het gebruik van SDS ter ondersteuning van coördinatie: wanneer de redding van een slachtoffer wordt gecoördineerd door de bemiddeling van een *shared data space*, zal een beduidende vermindering plaatsvinden in responstijd en dodental, vergeleken met autonome coördinatie van de reddingsoperatie. Als de redding van een slachtoffer gecoördineerd wordt door een *shared data space*, zullen individuele bijdragen van redders aan lagere responstijd en dodental significant zijn bij grotere getallen van redders, wanneer deze worden vergeleken met autonome coördinatie van de reddingsoperatie.

Curriculum Vitae

Rafael A. González (Bogotá, 1976) obtained his degree in Systems Engineering in the year 2000 from Javeriana University in Bogotá, Colombia. After graduation, he was involved with teaching in the areas of Information Systems and Systems Theory. He then went on to obtain his MSc in Computer Science from the Delft University of Technology in The Netherlands in the year 2003, after being granted a scholarship from the Dutch government. He went back to Javeriana University as Assistant Professor in Information Systems and Software Engineering, in addition to serving as IT consultant for projects in the public and private sector. He took a leave from his position to carry out his PhD research in the Systems Engineering Section of the Technology, Policy and Management Faculty of the Delft University of Technology. His scientific papers have been published in international journals, including BPMJ, IJEGR and JIS, as well as international conferences, including HICSS and ICIS.